P. Parvatha Reddy

Climate Resilient Agriculture for Ensuring Food Security

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Foreword

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with focus on food and nutrition security
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Dr. Prem Nath
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We do not know which came first on earth whether food or human being. But it is true that human beings cannot survive without food and food can be produced by following suitable agriculture which is entirely dependent on natural resources and climate. The climate change has been there since centuries but was not noticed as it is done today. Today the visible effect of change in climate is affecting both the production of food and the healthy life of human beings.

Climate change is one of the greatest ecological, economic, and social challenges which we are facing today. The scientific evidence that human activities are contributing to climate change is compelling. The anthropogenic activities are resulting in an increased emission of radiatively active gases, viz. carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), popularly known as the "greenhouse gases" (GHGs). Increase of mean temperature; changes in rain patterns; increased variability both in temperature and rain patterns; changes in water availability; the frequency and intensity of "extreme natural events"; sea level rise and salinization; perturbations in ecosystems, all will have profound impacts on agriculture, forestry and fisheries. Climatic changes and increasing climatic variability are likely to aggravate the problem of future food security by exerting pressure on agriculture.

To cope up with climate change that is likely to be both rapid and unpredictable, agricultural systems must be resilient and able to adapt to change. Resilient agriculture systems are those that are more likely to maintain economic, ecological and social benefits in the face of dramatic exogenous changes such as climate change and price swings. In the light of possible global warming, plant breeders should probably place even more emphasis on development of heat and drought-resistant crops. Both crop architecture and physiology may be genetically altered to adapt to warmer environmental conditions. At the national and international levels, the needs of regions and people vulnerable to the effects of climate change on their food supply should be addressed.

It is essential to envisage experimental models for each of the climate change components.

Information obtained from climate change studies can help us to predict which components are most likely to become more problematic in the future. Modeling can never be a perfect science, but unless we figure out a way to build planets identical to earth on which to perform experiments, the virtual planets they describe will remain the best available laboratories for studying future climate change.

Climate change adaptation and mitigation in the agriculture sector will have to be pursued in the context of meeting projected global food production demands. Although there are practices that hold great potential for meeting both needs, there is as yet neither international agreement nor national policy framework within which to operate. Given this situation, early action holds great potential for countries to take positive action in the short run that can unfold national and international policy, finance, and science inputs required. Potential conflicts with the international trading system can be addressed with the continued maturation of global climate policy.

The present book written by Dr. P. Parvatha Reddy on *Climate Resilient Agriculture for Ensuring Food Security* provides some of the much needed information collected from some of the world's leading climate scientists. The book comprehensively deals with important aspects on climate change such as causes of climate change; agriculture as a source of greenhouse gases; impacts of climate change on agriculture; regional impacts; impact on crop protection (insect and mite pests, plant pathogens, nematodes, and weeds); adaptation; mitigation; and a road map ahead. Dr. Reddy deserves commendation for his hard work in bringing out this excellent contribution to the science of climate change in agriculture.

This book will be of immense value to policy makers, scientific community involved in teaching, research and extension activities. The material can also be used for teaching postgraduate courses.

Bangalore, India Dr. Prem Nath
June 18, 2014

Preface

Agriculture is the basic activity by which humans live and survive on the earth. Climate change is one of the greatest ecological, economic, and social challenges facing agriculture today. The scientific evidence that human activities are contributing to climate change is compelling, but society is increasingly seeking information about the nature of the evidence and what can be done in response to a changing climate. Climatic changes and increasing climatic variability are likely to aggravate the problem of future food security by exerting pressure on agriculture.

For the past some decades, the gaseous composition of earth's atmosphere is undergoing a significant change, largely through increased emissions from energy, industry and agriculture sectors; widespread deforestation as well as fast changes in land use and land management practices. These anthropogenic activities are resulting in an increased emission of radiatively active gases, viz. carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), popularly known as the "greenhouse gases" (GHGs). These GHGs trap the outgoing infrared radiations from the earth's surface and thus raise the temperature of the atmosphere.

The continued dependence of agricultural production on light, heat, water and other climatic factors, the dependence of much of the world's population on agricultural activities, and the significant magnitude and rapid rates of possible climate changes all combine to create the need for a comprehensive consideration of the potential impacts of climate on global agriculture. Assessing the impacts of climate change on agriculture is a vital task. In both developed and developing countries, the influence of climate on crops and livestock persists despite irrigation, improved plant and animal hybrids and the growing use of chemical fertilizers.

Climate change has already significantly impacted agriculture and is expected to further impact food production directly and indirectly. Increase of mean temperature, changes in rain patterns, increased variability both in temperature and rain patterns, changes in water availability, the frequency and intensity of 'extreme events', sea level rise and salinization and perturbations in ecosystems, all will have profound impacts on agriculture, forestry, livestock and fisheries.

Agriculture and food systems must improve and ensure food security, and to do so they need to adapt to climate change and natural resource pressures, and contribute to mitigating climate change. These challenges, being interconnected, have to be addressed simultaneously. Climate-resilient agriculture contributes to the achievement of sustainably increasing agricultural productivity and incomes, adapting and building resilience to climate change and reducing and/or removing greenhouse gases emissions, where possible.

The information on climate resilient agriculture for ensuring food security is very much scattered. There is no book at present which comprehensively and exclusively deals with the above aspects on agriculture emphasizing on ensuring food security. The present book deals with climate resilient agriculture for food security in detail using adaptation and mitigation measures. The present book is divided into 14 chapters such as Introduction, Causes of Climate Change, Agriculture as a Source of Greenhouse Gases, Impacts of Climate Change, Regional Impacts on Climate Change, Crop Protection, Insect and Mite Pests, Plant Pathogens, Nematode Pests, Weeds, Integrated Pest Management, Adaptation, Mitigation, and A Road Map Ahead. The book is extensively illustrated with excellent quality photographs enhancing the quality of publication. The book is written in lucid style, easy to understand language along with adoptable recommendations involving eco-friendly adaptation and mitigation measures.

This book will prove an invaluable source of reference for the policy makers, researchers, scientists and students engaged in climate change research. The book will stimulate further basic and applied research for promoting resilient agriculture. This book will be of immense value to scientific community as a whole, and scientists involved in teaching, research and extension activities in particular. The material can also be used for teaching post-graduate courses. Suggestions to improve the contents of the book are most welcome (E-mail: reddy_parvatha@yahoo.com). The publisher, Springer India (Pvt.) Ltd., New Delhi, India, deserves commendation for their professional contribution.

Bangalore, Karnataka, India P. Parvatha Reddy
June 18, 2014

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About the Author

Dr. P. Parvatha Reddy obtained his Ph.D. degree jointly from the University of Florida, USA, and the University of Agricultural Sciences, Bangalore.

Dr. Reddy served as the Director of the prestigious Indian Institute of Horticultural Research (IIHR) at Bangalore from 1999 to 2002 during which period the Institute was honored with “ICAR Best Institution Award”. He also served as the Head, Division of Entomology and Nematology at IIHR and gave tremendous impetus and direction to research, extension and education in developing bio-intensive integrated pest management strategies in horticultural crops. These technologies are being practiced widely by the farmers across the country since they are effective, economical, eco-friendly and residue-free. Dr. Reddy has about 34 years of experience working with horticultural crops and involved in developing an F1 tomato hybrid “Arka Varadan” resistant to root-knot nematodes.

Dr. Reddy has over 250 scientific publications to his credit, which also include 30 books. He has also guided two Ph.D. students at the University of Agricultural Sciences, Bangalore.

Dr. Reddy served as Chairman, Research Advisory Committee of Indian Institute of Vegetable Research, Varanasi; National Centre for Integrated Pest Management, New Delhi; National Research Centre for Citrus, Nagpur; and the Project Directorate of Biological Control, Bangalore. He served as a Member, QRT to review the progress of AICRP on Nematodes; AINRP on Betelvine; Central Tuber Crops Research Institute, Trivandrum; and AICRP on Tuber Crops. He also served as a Member of the Expert Panel for monitoring the research program of National Initiative on Climate Resilient Agriculture (NICRA) in the theme of Horticulture including Pest Dynamics and Pollinators. He is the Honorary Fellow of the Society for Plant Protection Sciences, New Delhi, Fellow of the Indian Phytopathological Society, New Delhi, and Founder President of the Association for Advancement of Pest Management in Horticultural Ecosystems (AAPMHE), Bangalore.

Dr. Reddy has been awarded with the prestigious “Association for Advancement Pest Management in Horticultural Ecosystems Award”, “Dr. G.I. D’souza Memorial Lecture Award”, “Prof. H.M. Shah Memorial Award” and “Hexamar Agricultural Research and Development Foundation Award” for his unstinted efforts in developing sustainable, bio-intensive and eco-friendly integrated pest management strategies in horticultural crops.

Dr. Reddy has organized “Fourth International Workshop on Biological Control and Management of *Chromolaena odorata*”, “National Seminar on Hitech Horticulture”, “First National Symposium on Pest Management in Horticultural Crops: Environmental Implications and Thrusts” and “Second National Symposium on Pest Management in Horticultural Crops: New Molecules and Biopesticides”.

1 Introduction

Abstract

In the last decade, an overwhelming consensus has emerged among scientists that the world has entered an era of rapid global climate change, much of which is attributable to greenhouse gas (GHG) emissions from human activity. Rapid global climate change is expected to impact agriculture by causing shifts in temperature, precipitation, soil quality, pest regimes, and seasonal growth patterns. The exact nature and degree of these changes for any given region will be difficult to predict. At the same time that the agricultural sector is impacted by climate change, research indicates that current agricultural activities are a significant source of greenhouse gases that aggravate climate disruption. The amount of GHGs emitted from an agricultural operation depends on its system and management.

To cope with climate change that is likely to be both rapid and unpredictable, agricultural systems must be resilient and able to adapt to change. Resilient agriculture systems are those that are more likely to maintain economic, ecological, and social benefits in the face of dramatic exogenous changes such as climate change and price swings. In the face of uncertainty, food production systems should be established which are diverse and relatively flexible, with integration and coordination of livestock and crop production.

Sustainable and organic agricultural systems can help reduce agricultural GHG emissions through energy conservation, lower levels of carbon-based inputs, lower use of synthetic fertilizer, and other features that minimize GHG emissions and sequester carbon in the soil. Agricultural land can serve as a sink for GHG emissions, especially through soil carbon sequestration, which could help moderate climate change. But agricultural land can serve as an effective GHG sink over the long term only if agricultural systems are adopted which improve overall soil quality and provide for relatively stable GHG reduction or sequestration. Agricultural crop and forage production system features include, among others, fertilizer use and efficiency, nitrogen sequestration, and overall GHG emissions of associated livestock production systems.

P.P. Reddy, *Climate Resilient Agriculture for Ensuring Food Security*,
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Keywords
Agriculture • Climate change • Food security • Climate-resilient agriculture • Impacts • Adaptation • Mitigation

Agriculture plays a crucial role in ensuring food security while also accounting for a significant share of the world's gross domestic product (GDP). It engages almost two-thirds of the workforce in gainful employment. Several industries such as sugar, textiles, jute, food, and milk processing depend on agricultural production for their requirement of raw materials.

On account of its close linkages with other economic sectors, agricultural growth has a multiplier effect on the entire economy. Presently, the threat of climate change poses a challenge for sustainable agricultural growth. This threat is compounded due to accumulated greenhouse gas emissions in the atmosphere, anthropogenically generated through long-term intensive industrial growth and high consumption lifestyles and preferences. While the developing countries are collectively engaging themselves to deal with this threat, developing countries need to evolve a national strategy for adapting to climate change and its variabilities in order to ensure ecological sustainability in their socioeconomic developmental priorities.

Climate change refers to the statistical variations in the properties of the climate system such as changes in global temperatures, precipitation, etc., due to natural or human drivers over a long period of time. Climate change could drastically alter the distribution and quality of natural resources, thereby adversely affecting the livelihood security of the people.

Observations of Intergovernmental Panel on Climate Change (IPCC) indicate that the adverse impact of climate change due to rising temperatures and extreme weather events on the food production system could impact agricultural growth. Consistent warming trends and more frequent and intense extreme weather events are being observed across the world in the recent decades.

Significant negative impacts are being projected in the medium term (2010–2039) depending on the magnitude and distribution of warming. In the long run, the effect could even be more detrimental "if no adaptation measures are taken." The negative impact on agricultural production will imply significant percentage fall in the annual GDP. However, its fallout for livelihood security in the farming sector could be much more severe vis-à-vis other economic sectors.

Agriculture is crucial for ensuring the food and livelihood security of the country, and hence, it is important that this sector becomes resilient to increasing climatic variabilities and changes. A resilient agricultural production system is the prerequisite to sustain productivity in the event of extreme climatic variabilities. Although farmers have evolved many coping mechanisms over the years, these have fallen short of an effective response strategy in dealing with recurrent and intense forms of extreme events on the one hand and gradual changes in climate parameters including rise in surface temperatures, changes in rainfall patterns, increase in evapotranspiration rates, and degrading soil moisture conditions on the other. The need of the hour is, therefore, to synergize modern agriculture research with the indigenous wisdom of the farmers to enhance the resilience of agriculture to climate change. There is also a need to promote preservation of agricultural heritage to integrate in situ conservation of genetic resources based on traditional knowledge for natural resource management.

In order to sustain agricultural growth for meeting food requirements, policies and strategies need reorientation with appropriate response mechanisms that are embedded in the policy spectrum for not only meeting food grain and buffer stock requirements but also to ensure livelihood security in times of catastrophic incidents both natural and human driven.

While short-term mitigation measures would always demand immediate attention, the complexities of abiotic stress on crops and livestock in the long term would require intensive research to effectively address the adaptation processes required for making our production systems resilient to climate change.

1.1 What Is Climate Change?

Our atmosphere is full of invisible gases, some of which are greenhouse gases (GHGs). GHGs insulate the earth. They trap the sun's heat and keep our planet warm enough to sustain life. Some GHGs in our atmosphere do exist naturally. But a large portion of the GHGs in our atmosphere today have been, and continue to be, created by humans. This means that more of the sun's heat is being trapped than the earth actually needs. In fact, too much heat is being trapped, and the planet is warming too much. This is what is known as "global warming." Global warming is affecting weather patterns all over the world, and this effect is what is known as "climate change."

A region's climate means the usual weather patterns and conditions of a region. So, a change in weather patterns and conditions is a change in climate. The world's weather patterns are changing. This includes temperature changes (warming in some places and cooling in others) and altered rainfall patterns, as well as more frequent occurrences of hazardous weather events like heavy spring rains and heat waves. Changing climates pose risks to the health and safety of people, wildlife, forests, farms, and water supplies. Hence, it is so important for the government, farms, and food processing businesses to be aware of the causes of climate change and take corrective action. We all have a role to play in reducing GHG emissions.

Climate change is one of the greatest ecological, economic, and social challenges facing us today. The scientific evidence that human activities are contributing to climate change is compelling, but society is increasingly seeking information about the nature of the evidence and what can be done in response to a changing climate. This book provides some of that much-needed information collected from some of the world's leading climate scientists.

The terms "weather" and "climate" are frequently considered to be interchangeable, but weather and climate refer to different things. Weather is the brief, rapidly changing condition of the atmosphere at a given place and time, influenced by the movement of air masses. Climate, on the other hand, should more accurately be the term applied to the average weather conditions over longer periods of years to decades.

One may often hear mention of "climate variability" and "climate change" together. They are different facets of climate. Climate variability refers to the year-to-year variations, or noise, in the average conditions – meaning that consecutive summers, for example, will not all be the same, with some cooler and some warmer than the long-term average. Climate change refers to any long-term trends in climate over many years or decades, around which climate variability may be evident year on year. Hence, a single warmer or cooler year on its own is not a sufficient evidence to assert that climate is changing, but systematic changes in average conditions over many years do provide evidence of a changing climate.

The earth's climate has always changed, alternating between long periods of warm (interglacial) and cool (glacial) conditions, cycling over tens to hundreds of thousands of years. These changes are driven by both external influences and dynamics internal to the earth system. Key external influences include fluctuations in the amount of energy emitted by the sun and changes in the earth's orbit and axial tilt that affect the intensity and distribution of the sun's energy across the earth. Internal influences on climate include changes in the surface reflectivity due to the presence or absence of ice, changes in atmospheric composition of GHGs, variations in ocean currents, drifting continents, the cooling effect of volcanic dust, and other geological processes.

UNFCCC defines climate change as "a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods."

The IPCC defines climate change as a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period. Climate change may be due to natural internal processes or external forcings or persistent anthropogenic changes in the composition of the atmosphere or in land use.

Global climate change is a lasting change in the statistical distribution of weather patterns over periods ranging from decades to millions of years. It may be a change in average weather conditions or the distribution of events around the average (e.g., more or fewer extreme weather events). Climate change is a long-term shift in weather conditions identified by changes in temperature, precipitation, winds, and other indicators. Climate change can involve both changes in average conditions and changes in variability, including extreme events.

The earth's climate is naturally variable on all time scales. However, its long-term state and average temperature are regulated by the balance between incoming and outgoing energy, which determines the earth's energy balance. Any factor that causes a sustained change to the amount of incoming energy or the amount of outgoing energy can lead to climate change. As these factors are external to the climate system, they are referred to as "climate forcers," invoking the idea that they force or push the climate towards a new long-term state – either warmer or cooler depending on the cause of change.

Agriculture is the basic activity by which humans live and survive on the earth. Assessing the impacts of climate change on agriculture is a vital task. In both developed and developing countries, the influence of climate on crops and livestock persists despite irrigation, improved plant and animal hybrids, and the growing use of chemical fertilizers. The continued dependence of agricultural production on light, heat, water, and other climatic factors, the dependence of much of the world's population on agricultural activities, and the significant magnitude and rapid rates of possible climate changes all combine to create the need for a comprehensive consideration of the potential impacts of climate on global agriculture.

1.1.1 The Main Indicators of Climate Change

There are seven indicators that would be expected to increase in a warming world (Fig. 1.1):

- Temperature over land
- Ocean heat content
- Sea level
- Sea surface temperature
- Temperature over ocean
- Humidity
- Tropospheric temperature

There are three indicators that would be expected to decrease in a warming world (Fig. 1.1):

- Sea ice
- Snow cover
- Glaciers

1.1.2 Ten Key Indicators of a Human Finger Print on Climate Change

John Cook, writing the popular Skeptical Science blog, summarizes the key indicators of a human finger print on climate change (Fig. 1.2) as follows:

- Less heat escaping to space
- Shrinking thermosphere
- Cooling stratosphere
- Rising tropopause
- Less oxygen in the air
- More fossil fuel carbon in the air
- 30 billion tons of CO_2 per year
- More heat returning to earth
- Nights warming faster than days
- More fossil fuel carbon in coral

The information based on the comparison of atmospheric samples contained in ice cores and more recent direct measurements provides evidence that atmospheric CO_2 has increased since the industrial revolution.

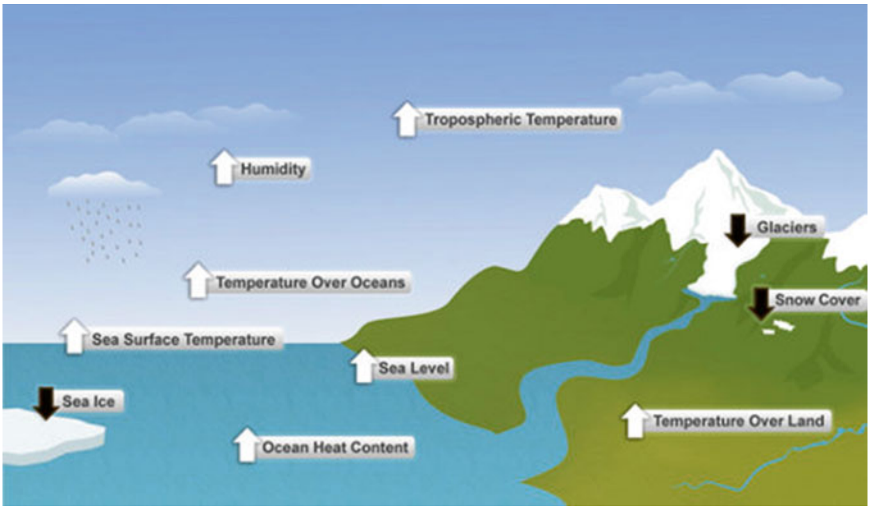

Fig. 1.1 Ten indicators for a warming world. Past decade warmest on record according to scientists in 48 countries

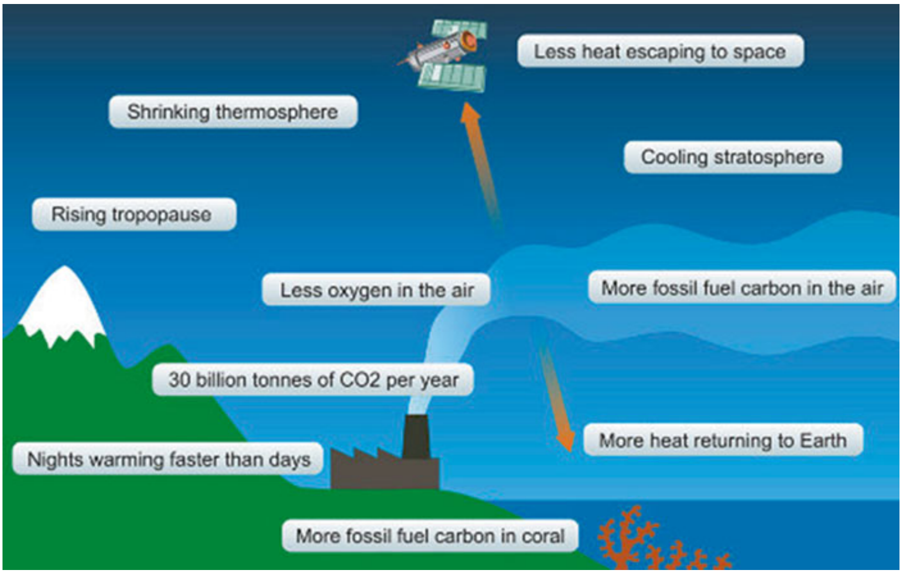

Fig. 1.2 Ten indicators of a human fingerprint on climate change

1.2 Causes of Climate Change

GHGs are released into the atmosphere by burning fossil fuels, clearing forests, and cement manufacture, and by many other industrial and agricultural activities, thereby increasing the amount of radiation trapped near the earth's surface and driving accelerated warming. This process, called the enhanced greenhouse effect, is caused by a forced release of GHGs from their terrestrial store into the atmosphere that has no precedent in history. The associated increases in global temperatures are changing fundamental climate processes. Some of those changes may be beneficial in some areas, but it is expected that most will cause more harm than good. Most of these human contributions to climate change have occurred over the last 200–300 years, following the agricultural and industrial revolutions.

Factors that cause climate change can be divided into two categories – those related to natural processes and those related to human activity. In addition to natural causes of climate change, changes internal to the climate system, such as variations in ocean currents or atmospheric circulation, can also influence the climate for short periods of time. This natural internal climate variability is superimposed on the long-term forced climate change.

1.2.1 Natural Causes

The earth's climate can be affected by natural factors that are external to the climate system, such as changes in volcanic activity, solar output, and the earth's orbit around the sun. Of these, the two factors relevant on timescales of contemporary climate change are changes in volcanic activity and changes in solar radiation. In terms of the earth's energy balance, these factors primarily influence the amount of incoming energy. Volcanic eruptions are episodic and have relatively short-term effects on climate. Changes in solar irradiance have contributed to climate trends over the past century, but since the industrial revolution, the effect of additions of GHGs to the atmosphere has been about ten times that of changes in the sun's output.

Solar radiation is the driving force of global climate. A portion of the radiation reaching the earth's surface is scattered or reflected by clouds, aerosols, dust, and other particles. Radiation reaching the planet is partly absorbed, causing the earth to emit thermal radiation, and part of the radiation is reflected back to the atmosphere. Water vapor and radiatively active CO_2, CH_4, N_2O, and O_3, among others, partly trap the reflected radiation to warm the surface temperature from a frigid 18 °C to about 15 °C, a natural phenomenon known as the "greenhouse effect." Human activities have contributed to an increase in the concentration of radiatively active gases and added new GHGs such as halocarbons (like chlorofluorocarbons) and hexafluoride (IPCC 1997). Together with changes in land cover, this may have contributed to an enhanced greenhouse effect to cause global warming and other climatic changes.

1.2.2 Human Causes

Climate change can also be caused by human activities, such as the burning of fossil fuels and the conversion of land for forestry and agriculture. Since the beginning of the industrial revolution, these human influences on the climate system have increased substantially. In addition to other environmental impacts, these activities change the land surface and emit various substances to the atmosphere. These in turn can influence both the amount of incoming energy and the amount of outgoing energy and can have both warming and cooling effects on the climate. The dominant product of fossil fuel combustion is carbon dioxide, a greenhouse gas. The overall effect of human activities since the industrial revolution has been a warming effect, driven primarily by emissions of carbon dioxide and enhanced by emissions of other GHGs.

The buildup of GHGs in the atmosphere has led to an enhancement of the natural greenhouse effect. It is this human-induced enhancement of the greenhouse effect that is of concern because ongoing emissions of GHGs have the potential to warm the planet to levels that have never been experienced in the history of human civilization. Such climate change could have far-reaching and/or unpredictable environmental, social, and economic consequences.

1.2.3 Biggest Threats of Climate Change

If the projected 2 °C rise in average temperatures comes to pass, then:

- Southern Europe may become too hot and arid to grow its present crops.
- Northern Europe will be the best place to grow typically Mediterranean crops.
- Scandinavia and Scotland may be the prime wine-producing areas.
- Much of Siberia will be a major cereal-growing area.
- Southern Africa could lose up to 30 % of its main staple crop – maize – by 2030.
- Yields for rainfed agriculture could be reduced by up to 50 % by 2020 (IPCC AR4).

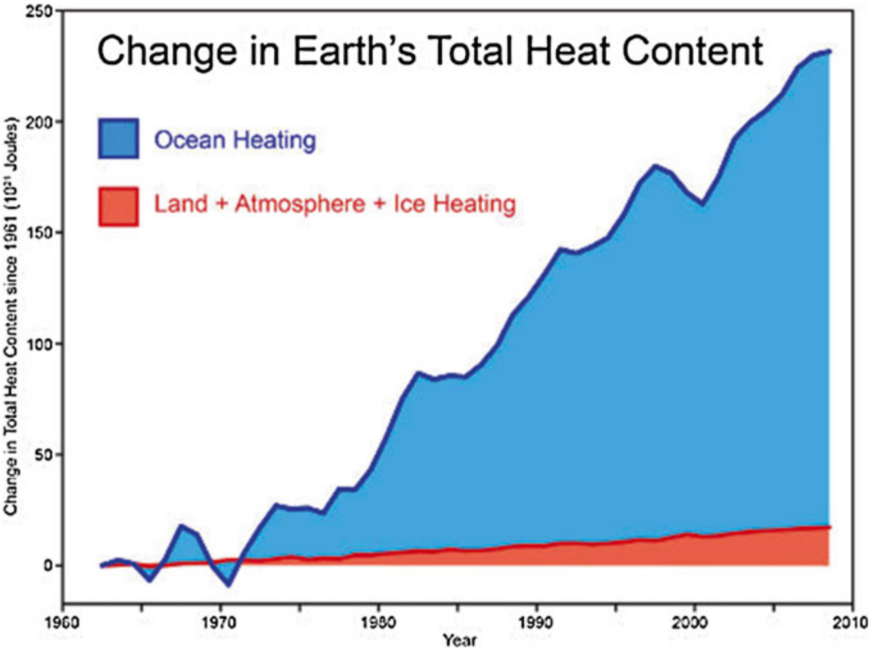

Fig. 1.3 The earth continues to build up heat (ocean, 93.4 %; atmosphere, 2.3 %; continents, 2.1 %; glaciers and ice caps, 0.9 %; Arctic sea ice, 0.8 %; Greenland ice sheet, 0.2 %; Antarctic ice sheet, 0.2 %)

The climate is changing and it is having an impact on agriculture production. One of the most impactful changes is water, either too much or too little of it in different areas of the world. It is projected that deserts and areas susceptible to drought will increase. At the same time, heavy precipitation events that often damage crops will become more frequent.

Effects of the climate change can be seen already. The southwestern region of the USA, for example, is very dry, whereas other regions have more rainfall and flooding. Wet springs delay the time for growing seeds, because it is too wet to plant. In other regions, the grounds warm up later than before which leaves less time for growing seeds.

Scientists predict that areas of the world that are hot and dry today – such as sub-Saharan Africa – will likely become hotter and drier in the future. Africa is one of the most seriously affected regions, where water scarcity and climate change disproportionately affect sub-Saharan Africa.

Most of the global warming is going into the oceans (Fig. 1.3). It takes time for the ocean to release its heat into the atmosphere. The world's northern freezer is on rapid defrost as large volumes of warm water are pouring into the Arctic Ocean, speeding the melt of sea ice. Indeed, the warming in the oceans has been occurring for quite some time.

Rapidly rising greenhouse gas concentrations are driving ocean systems towards conditions not seen for millions of years, with an associated risk of fundamental and irreversible ecological transformation. Changes in biological function in the ocean caused by anthropogenic climate change go far beyond death, extinctions, and habitat loss: fundamental processes are being altered, community assemblages are being reorganized, and ecological surprises are likely.

Global temperatures have warmed significantly since 1880, the beginning of what scientists call the "modern record." As greenhouse gas emissions from energy production, industry, and vehicles have increased, temperatures have climbed, most notably since the late 1970s.

1.3 Impacts of Climate Change

Historical records of temperature show that although temperatures vary naturally between ice ages and warm periods, there is no record of

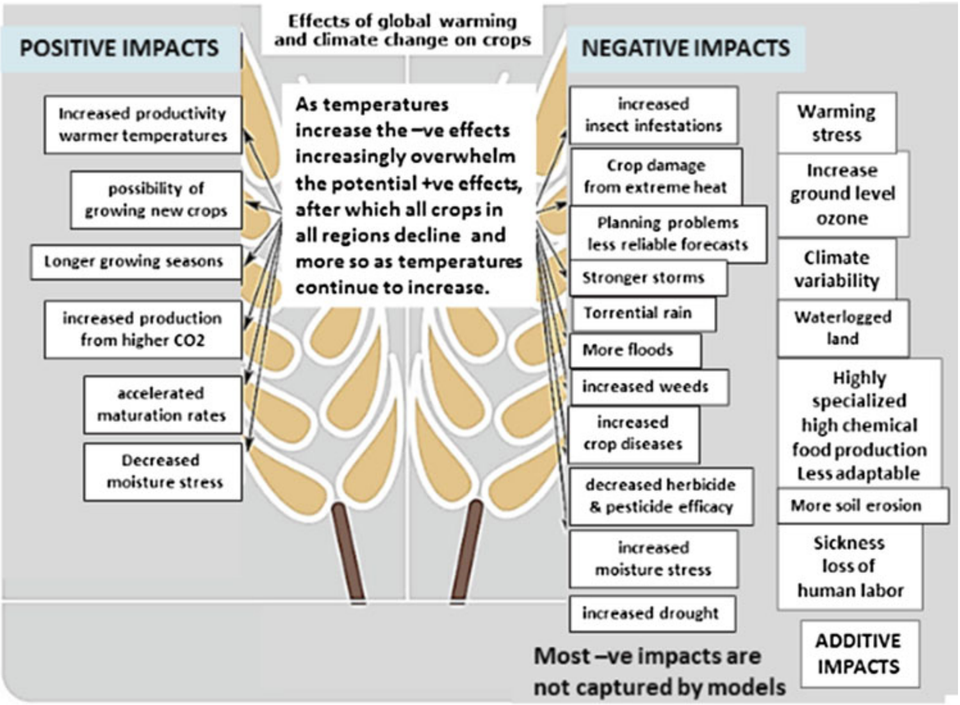

Fig. 1.4 Effects of climate change on crops

temperatures within human history ever having increased as rapidly as they have over the past 100 years. Many other aspects of the earth's climate also have changed over the past century or more. Some regions have become wetter, while others have suffered increased periods of drought. Frosts have decreased, and heat waves have increased, in many parts of the world. Mountain glaciers have shrunk and the sea level has risen.

Already over the last three decades, warming has had a discernible influence at the global scale on observed changes:

- Global warming
- Shifts in precipitation patterns
- Rising global mean sea level
- The retreat of glaciers
- Decline in the extent of Arctic sea ice coverage
- River runoff increases in global mean ocean temperatures
- Widespread melting of snow and ice sheets
- Increased flood risk for urban areas and ecosystems
- Ocean acidification
- Extreme climatic events including heat waves

The impacts of climate change on agriculture have significant repercussions on livelihoods, food production, and the overall economy of countries, particularly those with agriculture-based economies in the developing world. At the same time, the agricultural sector holds significant climate change mitigation potential through reductions of greenhouse gas (GHG) emissions as well as enhancement of agricultural sequestration (Fig. 1.4).

For the past some decades, the gaseous composition of the earth's atmosphere is undergoing a significant change, largely through increased emissions from energy, industry, and agriculture sectors; widespread deforestation; as well as fast changes in land-use and land management practices. These anthropogenic activities are resulting in an increased emission of radiatively active gases, viz., carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), popularly known as the "greenhouse gases" (GHGs) (Table 1.1). These

Table 1.1 Abundance and lifetime of greenhouse gases in the atmosphere

Parameters	CO_2	CH_4	N_2O	Chlorofluorocarbons
Average concentration 100 years ago (ppbV)	290,000	900	270	0
Current concentration (ppbV) (2007)	380,000	1,774	319	3–5
Projected concentration in the year 2030 (ppbV)	400,000–500,000	2,800–3,000	400–500	3–6
Atmospheric lifetime (year)	5–200	9–15	114	75
Global warming potential (100 years relative to CO_2)	1	25	298	4,750–10,900

Source: IPCC (2007)

GHGs trap the outgoing infrared radiations from the earth's surface and thus raise the temperature of the atmosphere. The global mean annual temperature at the end of the twentieth century, as a result of GHG accumulation in the atmosphere, has increased by 0.4–0.7 °C above that recorded at the end of the nineteenth century. The past 50 years have shown an increasing trend in temperature at 0.13 °C per decade, while the rise in temperature during the past one and half decades has been much higher. The Intergovernmental Panel on Climate Change has projected the temperature increase to be between 1.1 and 6.4 °C by the end of the twenty-first century (IPCC 2007). Global warming is expected to lead to other regional and global changes in the climate-related parameters such as rainfall, soil moisture, and sea level. Snow cover is also reported to be gradually decreasing. Therefore, concerted efforts are required for mitigation and adaptation to reduce the vulnerability of agriculture to the adverse impacts of climate change and making it more resilient.

The fourth assessment report of the IPCC indicates that agriculture will be affected both by long-term trends in mean temperature, precipitation, and winds and by increasing climate variability, associated with greater frequency and severity of extreme events such as droughts and floods. Changes in the hydrological cycle will affect agriculture in general and food production specifically. Changing wind speeds and directions will also affect crop and animal productivity.

At least 22 % of the area under the most important crops in the world is expected to suffer negative impacts from climate change by 2050. In sub-Saharan Africa and Asia, 56 % and 21 % of crops, respectively, are expected to be negatively affected. Impacts on livestock production are likely to be both direct, for example, productivity losses (physiological stress) owing to temperature increases, and indirect, for example, changes in the availability, quality, and prices of inputs such as fodder, energy, disease management, housing, and water. The distribution and virulence of pests and diseases of crops and livestock will change. New equilibrium in crop–pest–pesticide interactions will affect crop production. Changes in agrobiodiversity will have impacts, for example, on pollination. Crops in some areas may benefit from carbon fertilization, though evidence from field trials suggests yield effects may be lower than hoped. Climate change will also have impacts on the effectiveness of irrigation, nutritional value of foods, and safety in food storage and distribution.

The ability of most rural and urban communities to cope and adapt when confronted with economic and social shocks and changes is high, but needs ongoing, robust support. With increasing climate variability and shocks to agricultural food production, there are added disincentives for farmers to reinvest. Over time, this might lead to cumulative reductions in income and food security. Lack of reinvestment can diminish farmers', communities', and governments' abilities to meet the threshold levels of capital needed to transform farming systems in response to long-term climate shifts, for example, to change from a rice system to wheat or small grains. The combination of failing household risk management and failure to adapt to progressive climate change might entrench poverty traps and food insecurity. Farming systems and farmers will differ enormously in their capacities to respond to climate change. Differentiated adaptation strategies and enhanced climate risk management support to agriculture and farming households are critical to counter the impacts of climate change.

At the same time, our climate is being influenced by GHG emissions from agriculture, which is responsible for an estimated 10–12 % of total GHG emissions or as much as 30 % when considering land-use change, including deforestation driven by agricultural expansion for food, fiber, and fuel. The sector is responsible for 47 % of the world's methane (CH_4) and 58 % of its nitrous oxide (N_2O) emissions. Methane contributes 3.3 gigatons (Gt) of carbon dioxide equivalent (CO_2e) per year, primarily from enteric fermentation in livestock, and nitrous oxide contributes 2.8 Gt CO_2e per year, mainly as emissions from soils as a result of application of nitrogen fertilizers and as nitrogen excreted in livestock feces and urine. Carbon dioxide (CO_2) accounts for only a small proportion of agricultural emissions. Agricultural soils both emit and absorb large fluxes of carbon dioxide, resulting in a small net emission of 40 megatons (Mt) CO_2e, less than 1 % of global anthropogenic CO_2 emissions.

1.4 Food Security and Climate Change

Many countries worldwide are facing food crises due to conflict and disasters, while food security is being adversely affected by unprecedented price hikes for basic food, driven by historically low food stocks, high oil prices and growing demand for agrofuels, and droughts and floods linked to climate change. High international cereal prices have already sparked food riots in several countries. In addition, rural people (who feed the cities) are now, for the first time, less numerous than city dwellers and developing countries are becoming major emitters of greenhouse gases.

Many traditional equilibria are changing, such as those between food crops and energy crops and cultivated lands and rangelands, as is the nature of conflicts in general. These changing equilibria are, and will be, affected by changing climate, resulting in changed and additional vulnerability patterns.

The IPCC predicts that during the next decades, billions of people, particularly those in developing countries, will face changes in rainfall patterns that will contribute to severe water shortages or flooding, and rising temperatures that will cause shifts in crop growing seasons. This will increase food shortages and distribution of disease vectors, putting populations at greater health and life risks. The predicted temperature rise of 1–2.5 °C by 2030 will have serious effects, including reduced crop yield in tropical areas. The impact of a single climate-, water-, or weather-related disaster can wipe out years of gains in economic development.

Climate change will result in additional food insecurities, particularly for the resource poor in developing countries who cannot meet their food requirements through market access. Communities must protect themselves against the possibility of food-shortage emergencies through appropriate use of resources in order to preserve livelihoods as well as lives and property. It is imperative to identify and institutionalize mechanisms that enable the most vulnerable to cope with climate change impacts. This requires collaborative thinking and responses to the issues generated by the interaction of food security, climate change, and sustainable development.

Agriculture and food systems must improve and ensure food security, and to do so, they need to adapt to climate change and natural resource pressures and contribute to mitigating climate change. These challenges, being interconnected, have to be addressed simultaneously.

1.4.1 Food Security

One of the first planetary boundaries, perhaps the most important one, is that the world needs to feed itself. But today, almost one billion people are hungry. Another billion is malnourished, lacking essential micronutrients. While, globally, enough food is being produced to feed the entire world, one-third of it is lost or wasted, and low incomes and problems of distribution mean that accessibility to food is still out of reach for one out of six people on our planet. By 2050, food production has to increase, in quantity, quality, and diversity, especially in developing countries. Population and income growth will drive an ever-increasing demand, especially in developing countries (Foresight 2011a, b). Assuming these trends continue, FAO estimates that production has to increase by 60 % between now and 2050, especially in developing countries (Conforti 2011). Agriculture is also an essential driver of economic growth, particularly in rural areas and least developed countries. At the national level, boosting agricultural production stimulates overall economic growth and development, particularly in those countries with a high economic dependence on agriculture. According to the World Bank (2008), investment in agriculture is particularly efficient in creating new jobs. Agricultural and rural development acts as an engine for sustainable economic development, making an effective contribution to national economic growth. At the community level, agricultural development increases farm productivity, reduces food deficits, increases food surpluses, and raises incomes. Improved agriculture production provides opportunities to sustainably reduce poverty, food insecurity, and malnutrition and thereby improves livelihoods.

At the same time, food production and consumption already exerts a considerable impact on the environment (UNEP 2010; FAO 2012b). Food systems rely on resources, especially land, water, biodiversity, and fossil fuels, which are becoming ever more fragile and scarce.

Agriculture is essential for a green economy. In fact, FAO considers that there can be no green economy without agriculture. This is why FAO proposed "Greening Economy with Agriculture" as the basis key message for Rio+20 (FAO 2012b).

1.4.2 Green Economy

Green economy is defined as "An economy that results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities" (UNEP 2010). Practically speaking, a green economy is one whose growth in income and employment is driven by investments that simultaneously:

- Reduce carbon emissions and pollution.
- Enhance energy and resource-use efficiency.
- Prevent the loss of biodiversity and ecosystem services.

As per the definition of the concept, green economy objectives should resonate with sustainable development agendas, highlighting a concern with human well-being and social equity – both now and for future generations – as well as balancing risks and scarcities faced by peoples across the globe. As stated in the outcome document of the Rio+20 conference, the "green economy in the context of sustainable development and poverty eradication will enhance our ability to manage natural resources sustainably and with lower negative environmental impacts, increase resource efficiency, and reduce waste."

Climate-resilient agriculture contributes to the goals of making sustainable development concrete. It integrates the three dimensions of sustainable development in addressing food security and climate concerns in a forward-looking perspective. It is guided by the need for more resource efficiency and resilience. These principles are also central in the Rio+20 outcome documents, which recognize resource efficiency as key to a green economy and affirm the need to enhance agriculture's resilience.

1.4.3 Ensuring Food Security

The world is producing enough food, but in 2010–2012, there were still almost 870 million people estimated to be undernourished (FAO 2012a). In addition, another billion people are malnourished, lacking essential micronutrients. The paradox is that at the same time, a large number of people, mainly in richer countries, are overeating causing long-term health problems and that 60 % of the malnourished actually are food producers, smallholders, and pastoralists, with 20 % living in cities and 20 % landless rural people. For the poor producers, food is not only a basic need, it is the single, and often fragile, support they have for maintaining their livelihood. What is true at the household level is also true at the macroeconomic level. There are 32 countries, 20 of them in Africa, facing food crises and in need of international emergency support. In most of these countries, paradoxically, agriculture is an important, if not the major, part of economy.

The objective is to ensure food and nutrition security, worldwide. Ensuring availability of calories and sufficient global production is not enough; we also need to make sure that enough food is accessible to everyone, everywhere, physically and economically. In addition, we need to ensure that this food is properly utilized in the right quality and diversity. The goal is to ensure the stability of these three components of food and nutrition security: availability, access, and utilization.

Between now and 2050, the world's population will increase by one-third. Most of the additional 2 billion people will live in developing countries. At the same time, more people will be living in cities (70 % against the current 50 %). Urbanization and rising incomes in developing countries are driving increases in the consumption of animal products (FAO 2009). Given these trends, FAO estimates that production will have to increase by 60 % by 2050 to satisfy the expected demands for food and feed (Conforti 2011). Demand for biofuels, another important factor for the global market, is very dependent on national policies and global demand is expected to grow. According to the OECD-FAO projections, because of increasing mandates and consumption incentives, biofuel production is expected to double between 2005 and 2019 (OECD 2010 and FAO 2010).

To achieve food security and agricultural development goals, adaptation to climate change and lower emission intensities per output will be necessary. This transformation must be accomplished without depletion of the natural resource base. Climate change is already having an impact on agriculture and food security as a result of increased prevalence of extreme events and increased unpredictability of weather patterns. This can lead to reductions in production and lower incomes in vulnerable areas. These changes can also affect global food prices. Developing countries and smallholder farmers and pastoralists in particular are being especially hard hit by these changes. Many of these small-scale producers are already coping with a degraded natural resource base. They often lack knowledge about potential options for adapting their production systems and have limited assets and risk-taking capacity to access and use technologies and financial services.

Enhancing food security while contributing to mitigate climate change and preserving the natural resource base and vital ecosystem services requires the transition to agricultural production systems that are more productive, use inputs more efficiently, have less variability and greater stability in their outputs, and are more resilient to risks, shocks, and long-term climate variability. More productive and more resilient agriculture requires a major shift in the way land, water, soil nutrients, and genetic resources are managed to ensure that these resources are used more efficiently. Making this shift requires considerable changes in national and local governance, legislation, policies, and financial mechanisms. This transformation will also involve improving producers' access to markets. By reducing greenhouse gas emissions per unit of land and/or agricultural product and increasing carbon sinks, these changes will contribute significantly to the mitigation of climate change.

1.5 Climate-Resilient Agriculture

Since climate change poses complex challenges like multiple abiotic stresses on crops and livestock, shortage of water, land degradation, and loss of biodiversity, a focused and long-term research is required to find solutions to the problems. The necessary infrastructure to carry out basic and strategic research has to be put in place. At the same time, there is a scope to improve the resilience of agriculture by application of existing knowledge and technology on farmers' field as a holistic package. Hence, there is a need to develop improved technologies through short-term and long-term research and also demonstrate the existing technologies on farmers' fields for enhancing the resilience.

Sustainable agriculture seeks to transform agriculture into an ecologically sustainable climate-resilient production system while at the same time exploiting its fullest potential and thereby ensuring food security and equitable access to food resources, enhancing livelihood opportunities, and contributing to economic stability. Climate-resilient agriculture (CRA) contributes to the achievement of sustainable development goals. It integrates the three dimensions of sustainable development (economic, social, and environmental) by jointly addressing food security and climate challenges. It is composed of three main pillars:

- Sustainably increasing agricultural productivity and incomes
- Adapting and building resilience to climate change
- Reducing and/or removing greenhouse gases emissions, where possible

CRA is an approach to developing the technical, policy, and investment conditions to achieve sustainable agricultural development for food security under climate change. The magnitude, immediacy, and broad scope of the effects of climate change on agricultural systems create a compelling need to ensure comprehensive integration of these effects into national agricultural planning, investments, and programs. The CRA approach is designed to identify and operationalize sustainable agricultural development within the explicit parameters of climate change.

Achieving the transformations required for CRA and meeting these multiple objectives require an integrated approach that is responsive to specific local conditions. Coordination across agricultural sectors (e.g., crops, livestock, forestry, and fisheries) as well as other sectors, such as with energy and water sector development, is essential to capitalize on potential synergies, reduce trade-offs, and optimize the use of natural resources and ecosystem services.

This approach also aims to strengthen livelihoods and food security, especially of smallholders, by improving the management and use of natural resources and adopting appropriate methods and technologies for the production, processing, and marketing of agricultural goods. To maximize the benefits and minimize the trade-offs, CRA takes into consideration the social, economic, and environmental context where it will be applied. Repercussions on energy and local resources are also assessed. A key component is the integrated landscape approach that follows the principles of ecosystem management and sustainable land and water use.

1.6 Climate Change Adaptation

Climate change adaptation involves taking action to adjust to, or respond to, the effects of changes in climate, such as reduced rainfall or rising sea level. Adaptations to climate change exist at the various levels of agricultural organization. In temperate regions, farm-level adaptations include changes in planting and harvest dates, tillage and rotation practices, substitution of crop varieties or species more appropriate to the changing climate regime, increased fertilizer or pesticide applications, and improved irrigation and drainage systems. Governments can facilitate adaptation to climate change through water development projects, agricultural extension activities, incentives, subsidies, regulations, and provision of crop insurance. There is considerable scope for agricultural adaptation throughout the food chain, for example, better postharvest storage and distribution of food, to ameliorate the gap between good and poor years.

Easterling et al. (2007) describe a range of options, at the level of autonomous adaptation, for cropping and livestock systems:

- Different varieties or species with greater resistance to heat or water stress or adapted phenology (maturation times and responses)
- New cropping practices, including adjustments in timing and locality of crop production, and changed water and fertilizer management to maintain yield quality and quantity
- Greater use of water conservation technologies, including those to harvest water and conserve soil moisture or, in flood-prone areas, water management to prevent water logging, erosion, and nutrient leaching
- Diversification of on-farm activities and enhancement of agrobiodiversity, with greater integration between livestock and cropping systems

- Adapted livestock and pasture management, including rematching stocking rates and timing with pasture production, new varieties and species of forage and livestock, updated fertilizer applications, and using supplementary feeds and concentrates
- Improved management of pests, diseases, and weeds, for example, through integrated pest management, new crop and livestock varieties, improved quarantine, and sentinel monitoring programs
- Better use of short-term and seasonal climate forecasting to reduce production risk

1.7 Climate Change Mitigation

Climate change mitigation refers to actions that aim to reduce the amount of climate change, typically by limiting the future increases in concentrations of greenhouse gases in the atmosphere – either by reducing emissions from a wide range of our industrial and agricultural activities or by increasing the amount of CO_2 taken up and stored in natural "sinks" such as forests and soils. Actions that reduce greenhouse gas emissions in many cases also improve our preparedness for future climate change.

Smith et al. (2007) distinguish seven broad sets of options for mitigating GHG emissions from agricultural ecosystems:

- Cropland management, including nutrient management, tillage and residue management, water management (irrigation, drainage), rice paddy management, agro-forestry, set-asides, crop rotations, and land-use change
- Grazing land management and pasture improvement, including grazing intensity, increased productivity (e.g., fertilization), nutrient management, fire management, and species introduction (including legumes)
- Management of organic soils, including avoiding drainage of wetlands
- Restoration of degraded lands, including erosion control, organic amendments, and nutrient amendments
- Livestock management, including improved feeding practices, dietary additives, longer-term structural and management changes, and animal breeding
- Manure management, including improved storage and handling, anaerobic digestion, and more efficient use as a nutrient source
- Bioenergy, including energy crops (solid, liquid, biogas, and residues)

The potential for synergies among these land-based agricultural mitigation actions that promote food security is particularly high for specific practices such as adopting improved crop varieties (e.g., with higher water-use efficiency), breeding livestock to increase sustainable productivity of meat or milk, avoiding bare fallow land and changing crop rotations to incorporate food-producing cover crops and legumes, adopting precision fertilizer management, improving forage quality and quantity on pastures, expanding energy-efficient irrigation and water conservation techniques (e.g., in rice systems), and implementing agro-forestry that does not take significant amounts of land out of food production.

Technical options for mitigation in agriculture need to be locally appropriate. For example, although land management presents the major opportunity for mitigation in the agricultural sector globally, other interventions, such as improved livestock breeding and feeding, or manure management, may be more effective for particular countries, farming systems, or agroecological zones.

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Causes of Climate Change

2

Abstract

Scientists in the world have reached an overwhelming consensus that climate change is real and caused primarily by human activity. Greenhouses gases, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) trap heat in the atmosphere and regulate our climate. Greenhouse gases act like a blanket. The thicker the blanket, the warmer our planet becomes. At the same time, the earth's oceans are also absorbing some of this extra carbon dioxide, making them more acidic and less hospitable for sea life. The increase in global temperature is significantly altering our planet's climate, resulting in more extreme and unpredictable weather. For instance, heat waves are becoming more frequent and many places are experiencing record droughts followed by intense rainfalls.

Burning fossil fuels, such as coal, oil, and natural gas, to generate energy has the greatest impact on the atmosphere than any other single human activity. Globally, power generation is responsible for about 23 billion tons of CO_2 emissions per year – in excess of 700 tons every second. Coal is especially damaging to our atmosphere, releasing 70 % more carbon dioxide than natural gas for every unit of energy produced.

Forests help protect the planet by absorbing massive amounts of CO_2, the most abundant type of pollution that causes climate change. Unfortunately, forests are currently being destroyed or damaged at an alarming rate. Logging and clearing land for agriculture or livestock release huge amounts of carbon dioxide and other harmful greenhouse gases into the atmosphere. It also diminishes those regions' ability to absorb carbon pollution.

Keywords

Greenhouse gases • Carbon dioxide • Methane • Burning of fossil fuels • Deforestation

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The earth's climate is dynamic and always changing through a natural cycle. What the world is more worried about is that the changes that are occurring today have been speeded up because of man's activities. These changes are being studied by scientists all over the world who are finding evidence from tree rings, pollen samples, ice cores, and sea sediments. The causes of climate change can be divided into two categories – those that are due to natural causes and those that are created by man.

2.1 Natural Causes

There are a number of natural factors responsible for climate change. Some of the more prominent ones are continental drift, volcanoes, ocean currents, the earth's tilt, and comets and meteorites.

2.1.1 Continental Drift

Something peculiar has been noticed about South America and Africa on a map of the world – they seem to fit into each other like pieces in a jigsaw puzzle. About 200 million years ago, they were joined together. Scientists believe that back then, the earth was not as we see it today, but the continents were all part of one large landmass. Proof of this comes from the similarity between plant and animal fossils and broad belts of rocks found on the eastern coastline of South America and western coastline of Africa, which are now widely separated by the Atlantic Ocean. The discovery of fossils of tropical plants (in the form of coal deposits) in Antarctica has led to the conclusion that this frozen land, at some time in the past, must have been situated closer to the equator, where the climate was tropical, with swamps and plenty of lush vegetation.

The continents that we are familiar with today were formed when the landmass began gradually drifting apart, millions of years back. This drift also had an impact on the climate because it changed the physical features of the landmass, their position, and the position of water bodies. The separation of the landmasses changed the flow of ocean currents and winds, which affected the climate. This drift of the continents continues even today; the Himalayan range is rising by about 1 mm every year because the Indian land mass is moving towards the Asian land mass, slowly but steadily.

2.1.2 Volcanoes

When a volcano erupts, it throws out large volumes of sulfur dioxide (SO_2), water vapor, dust, and ash into the atmosphere. Although the volcanic activity may last only a few days, yet the large volumes of gases and ash can influence climatic patterns for years. Millions of tons of sulfur dioxide gas can reach the upper levels of the atmosphere (called the stratosphere) from a major eruption. The gases and dust particles partially block the incoming rays of the sun, leading to cooling. Sulfur dioxide combines with water to form tiny droplets of sulfuric acid. These droplets are so small that many of them can stay aloft for several years. They are efficient reflectors of sunlight and screen the ground from some of the energy that it would ordinarily receive from the sun. Winds in the upper levels of the atmosphere, called the stratosphere, carry the aerosols rapidly around the globe in either an easterly or westerly direction. Movement of aerosols north and south is always much slower. This should give you some idea of the ways by which cooling can be brought about for a few years after a major volcanic eruption.

Mount Pinatubo volcano in the Philippines erupted in April 1991 emitting thousands of tons of gases into the atmosphere. Volcanic eruptions of this magnitude can reduce the amount of solar radiation reaching the earth's surface, lowering temperatures in the lower levels of the atmosphere (called the troposphere) and changing atmospheric circulation patterns. The extent to which this occurs is an ongoing debate.

Another striking example was in the year 1816, often referred to as "the year without a summer." Significant weather-related disruptions occurred in New England and in Western Europe with killing summer frosts in the USA and

Canada. These strange phenomena were attributed to a major eruption of the Tambora volcano in Indonesia in 1815.

2.1.3 The Earth's Tilt

The earth makes one full orbit around the sun each year. It is tilted at an angle of 23.5° to the perpendicular plane of its orbital path. For one half of the year when it is summer, the northern hemisphere tilts towards the sun. In the other half when it is winter, the earth is tilted away from the sun. If there was no tilt, we would not have experienced seasons. Changes in the tilt of the earth can affect the severity of the seasons – more tilt means warmer summers and colder winters; less tilt means cooler summers and milder winters.

The earth's orbit is somewhat elliptical, which means that the distance between the earth and the sun varies over the course of a year. We usually think of the earth's axis as being fixed, after all, it always seems to point towards Polaris (also known as the Polestar and the North Star). Actually, it is not quite constant: the axis does move, at the rate of a little more than a half-degree each century. So Polaris has not always been, and will not always be, the star pointing to the North. When the pyramids were built, around 2500 BC, the pole was near the star Thuban (Alpha Draconis). This gradual change in the direction of the earth's axis, called precession, is responsible for changes in the climate.

2.1.4 Ocean Currents

The oceans are a major component of the climate system. They cover about 71 % of the earth and absorb about twice as much of the sun's radiation as the atmosphere or the land surface. Ocean currents move vast amounts of heat across the planet – roughly the same amount as the atmosphere does. But the oceans are surrounded by land masses, so heat transport through the water is through channels.

Winds push horizontally against the sea surface and drive ocean current patterns. Certain parts of the world are influenced by ocean currents more than others. The coast of Peru and other adjoining regions are directly influenced by the Humboldt current that flows along the coastline of Peru. The El Niño event in the Pacific Ocean can affect climatic conditions all over the world.

Another region that is strongly influenced by ocean currents is the North Atlantic. If we compare places at the same latitude in Europe and North America, the effect is immediately obvious. Take a closer look at this example – some parts of coastal Norway have an average temperature of −2 °C in January and 14 °C in July, while places at the same latitude on the Pacific coast of Alaska are far colder: −15 °C in January and only 10 °C in July. The warm current along the Norwegian coast keeps much of the Greenland-Norwegian Sea free of ice even in winter. The rest of the Arctic Ocean, even though it is much further south, remains frozen.

Ocean currents have been known to change direction or slow down. Much of the heat that escapes from the oceans is in the form of water vapor, the most abundant greenhouse gas on earth. Yet, water vapor also contributes to the formation of clouds, which shade the surface and have a net cooling effect.

2.2 Human Causes

Climate change can also be caused by human activities, such as the burning of fossil fuels and the conversion of land for forestry and agriculture. Since the beginning of the industrial revolution, these human influences on the climate system have increased substantially. In addition to other environmental impacts, these activities change the land surface and emit various substances to the atmosphere. These in turn can influence both the amount of incoming energy and the amount of outgoing energy and can have both warming and cooling effects on the climate. The dominant product of fossil fuel combustion is carbon dioxide, a greenhouse gas. The overall effect of human activities since the industrial revolution has been a warming effect, driven primarily by emissions of

Table 2.1 Atmospheric concentration, lifetime, and global warming potential (GWP) of major greenhouse gases (IPCC 2007b)

		Lifetime GWP	
Greenhouse gas	Atmospheric concentration	(years)	(100 years)
Carbon dioxide	387 ppm	Variable	1
Methane	1,780 ppb	12	25
Nitrous oxide	319 ppb	114	298
CFC 11	250 ppt	45	4,600
CFC 12	533 ppt	100	10,600
HCFC 22	132 ppt	11.9	1,700
HFC 23	12 ppt	260	12,000

carbon dioxide and enhanced by emissions of other greenhouse gases.

The sunlight enters a greenhouse through the transparent glass or plastic and heats the plants, but the heat emitted by the plants in the form of infrared radiations cannot pass through the glass or plastic roof and walls of the greenhouse. As a result, temperature inside the greenhouse rises. The phenomenon is known as "greenhouse effect." In a similar manner, the earth's atmosphere, which acts like the glass or plastic roof and walls of a greenhouse, allows most of incoming sunlight to pass through and heat the surface. But the heat radiated by the heated surface cannot pass freely into the space because of the presence of a number of gases such as carbon dioxide, methane, ozone, nitrous oxide, and water vapor in the atmosphere. Consequently, the average temperature of the earth's atmosphere is increasing – a phenomenon which is commonly known as global warming. It has been found that carbon dioxide contributes 60 %, methane 15 %, and nitrous oxide 5 % to the global warming (IPCC 2007b). Also, as a heat-trapping gas, methane is 25 times and nitrous oxide is 298 times more effective than carbon dioxide (Table 2.1).

The buildup of greenhouse gases in the atmosphere has led to an enhancement of the natural "greenhouse effect" (Fig. 2.1). It is this human-induced enhancement of the greenhouse effect that is of concern because ongoing emissions of greenhouse gases have the potential to warm the planet to levels that have never been experienced in the history of human civilization. Such climate change could have far-reaching and/or unpredictable environmental, social, and economic consequences.

The earth would be much colder if not for the "greenhouse" gases that provide a blanket that warms the atmosphere. Some of the gases in the atmosphere transmit the short-wave radiation from the sun to the earth, warming its surface. Some of this warmth is emitted in the form of long-wave (infrared) radiation from the earth to the atmosphere, and some of the gases in the atmosphere absorb and reemit radiation of this wavelength, effectively enhancing the warming of the lower atmosphere. These gases are called greenhouse gases because their effect is similar to the function of a glass greenhouse that heats up as infrared radiation is trapped by the glass. The main greenhouse gases are water vapor, carbon dioxide, methane, and nitrous oxide, all of which occur naturally in the atmosphere. Most of these human contributions to climate change have occurred over the last 200–300 years, following the agricultural and industrial revolutions.

2.3 Greenhouse Gases

The three main causes of the increase in greenhouse gases observed over the past 250 years have been fossil fuels, land use, and agriculture (Fig. 2.2) (IPCC 2007a). Six main greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Water vapor is also considered a greenhouse gas.

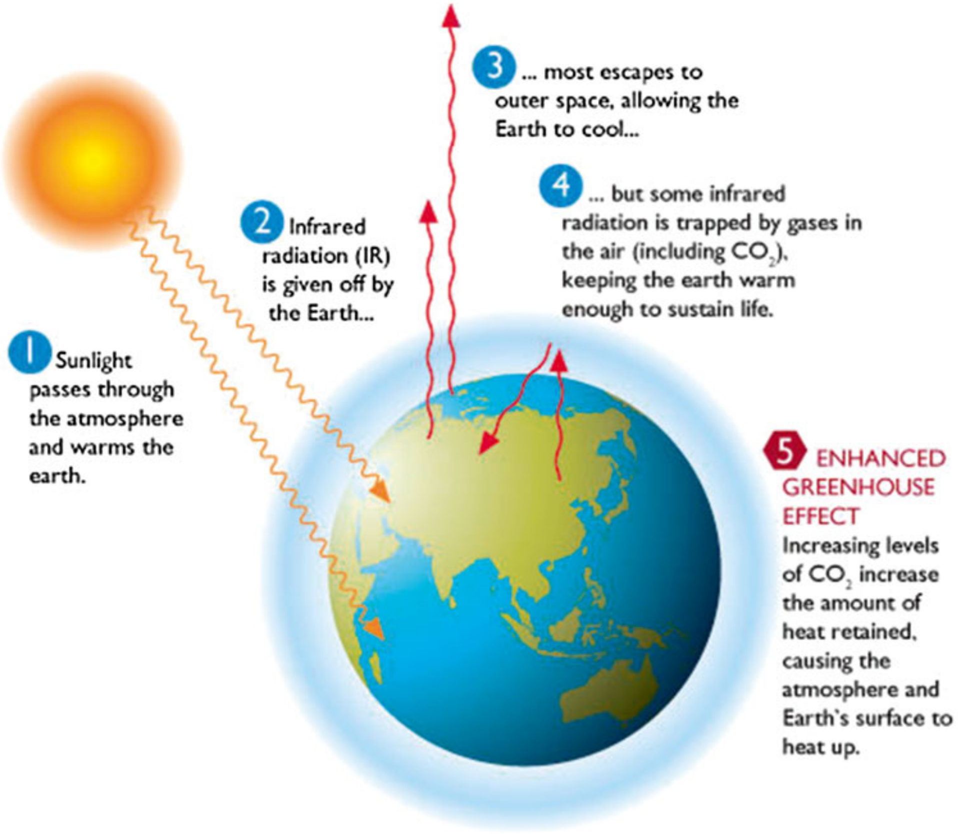

Fig. 2.1 Graphical representation of the greenhouse effect (Source: CO_2 Cooperative Research Centre)

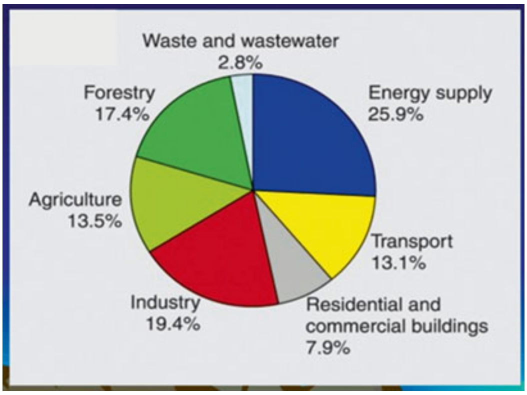

Fig. 2.2 Contribution of different sectors in the world to climate change (Sources of greenhouse gas emissions)

The contribution of each of the greenhouse gases to global warming is dependent on its global warming potential (GWP), expressed as carbon dioxide equivalent (CO_2e). The GWP takes into account:

- The amount of radiation that the gas absorbs and the wavelength at which it absorbs
- The time that the gas stays in the atmosphere before reacting or being dissolved in rainwater or the ocean
- The current concentration of the gas in the atmosphere
- Any indirect effects of the gas (e.g., methane will produce ozone gas in the lower atmosphere and water vapor in the stratosphere)

The GWP of methane is 25 times as potent a greenhouse gas as carbon dioxide, and nitrous oxide is 298 times as potent a greenhouse gas as carbon dioxide.

2.3.1 Water Vapor

Water vapor is the most abundant greenhouse gas, but importantly, it acts as a feedback to the climate.

Fig. 2.3 Carbon dioxide emissions from industries

It increases as the earth's atmosphere warms, but so does the possibility of clouds and precipitation, making these some of the most important feedback mechanisms to the greenhouse effect. Much of the heat that escapes from the oceans is in the form of water vapor, the most abundant greenhouse gas on earth. Yet, water vapor also contributes to the formation of clouds, which shade the surface and have a net cooling effect.

2.3.2 Carbon Dioxide (CO_2)

Carbon dioxide is undoubtedly the most important greenhouse gas in the atmosphere. A minor but very important component of the atmosphere, CO_2 is released through natural processes such as respiration and volcano eruptions and through human activities such as deforestation, land-use changes, land clearing, agriculture, burning fossil fuels, and other activities. The main sources of CO_2 are decay of organic matter, forest fires, eruption of volcanoes, burning of fossil fuels, deforestation, and land-use change, whereas plants, oceans, and atmospheric reactions are the major sinks. Though agricultural soil is a small contributor of carbon dioxide, factors such as soil texture, temperature, moisture, pH, and available C and N contents influence CO_2 emission from soil. Humans have increased atmospheric CO_2 concentration by a third since the industrial revolution began. This is the most important long-lived "forcing" of climate change.

The industrial activities that our modern civilization depends upon have raised atmospheric CO_2 levels from preindustrial value of 280 parts per million to 389 parts per million in 2010. Without mitigation measures, the concentration of CO_2 in the atmosphere is predicted to rise to at least 650 ppm and up to 1,200 ppm by 2100 (IPCC 2001), which is expected to increase average global temperature by 1–6 °C (Fig. 2.3).

When we mine coal and extract oil from the earth's crust and then burn these fossil fuels for transportation, heating, cooking, electricity, and manufacturing, we are effectively moving carbon more rapidly into the atmosphere than is being removed naturally through the sedimentation of carbon, ultimately causing atmospheric carbon dioxide concentrations to increase. Burning fossil fuels, such as coal, oil, and natural gas, to generate energy has the greatest impact on the atmosphere than any other single human activity. Globally, power generation is responsible for about 23 billion tons of CO_2 emissions per year – in excess of 700 ton every second. Coal is especially damaging to our atmosphere, releasing 70 % more carbon dioxide than natural gas for every unit of energy produced.

Forests help to protect the planet by absorbing massive amounts of carbon dioxide (CO_2), the most abundant type of pollution that causes climate change. Unfortunately, forests are currently being destroyed or damaged at an alarming rate. By clearing forests to support

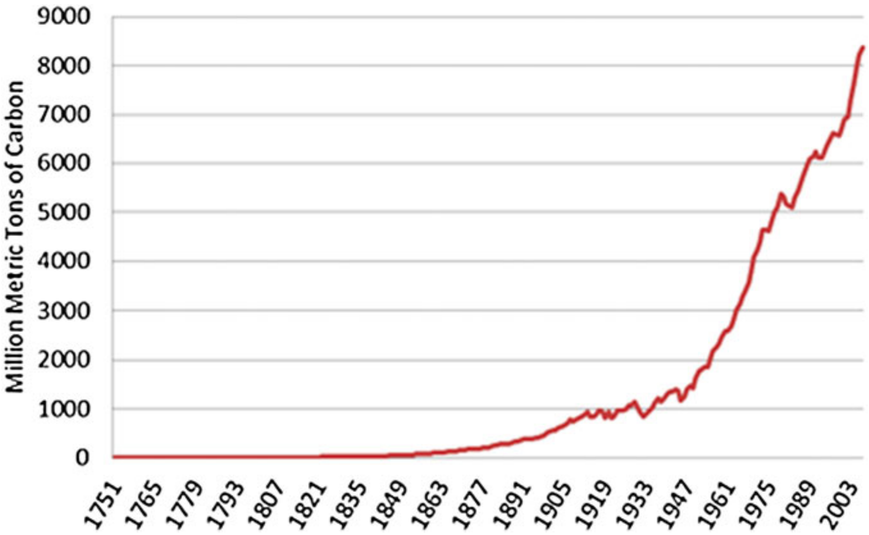

Fig. 2.4 Global CO_2 emissions, 1751–2003 [Carbon Dioxide Information Analysis Center (CDIAC), August 2010]

agriculture, we are transferring carbon from living biomass into the atmosphere (dry wood is about 50 % carbon).

Logging and clearing land for agriculture or livestock release huge amounts of carbon dioxide and other harmful greenhouse gases into the atmosphere. It also diminishes those regions' ability to absorb carbon pollution.

The result is that humans are adding ever-increasing amounts of extra carbon dioxide into the atmosphere. Because of this, atmospheric carbon dioxide concentrations are higher today than they have been over the last half-million years or longer.

CO_2 emissions from manufacture of fertilizers and pesticides add to the overall carbon footprint of agriculture. For example, industrial fertilizer production is estimated to emit 6.7 kg CO_2e per kg N manufactured.

Atmospheric CO_2 levels have dramatically increased in recent years. If we "zoom" in on just the past 250 years, we see the increasing trend (Fig. 2.4).

Carbon dioxide is an inorganic form of carbon cycled through photosynthesis and respiration (Fig. 2.5). The cycle of photosynthesis and respiration is crucial to sustaining life so it is the other processes which release carbon dioxide which need to be addressed.

2.3.3 Methane (CH_4)

Methane is another important greenhouse gas in the atmosphere. Wetlands, organic matter decay, cattle and refuse landfills, termites, and natural gas and oil extraction are the main sources of methane, whereas escape into the stratosphere and adsorption by soil are the main sinks. The primary sources of methane emission in agriculture include rice cultivation, biomass burning, animal digestive processes, and manure storage and handling. About ¼ of all methane emissions are said to come from domesticated animals such as dairy cows, goats, pigs, buffaloes, camels, horses, and sheep. These animals produce methane during the cud-chewing process. Methane is also released from rice or paddy fields that are flooded during the sowing and maturing periods. When soil is covered with water, it becomes anaerobic or lacking in oxygen. Under such conditions, methane-producing bacteria and other organisms decompose organic matter in the soil to form methane. Nearly 90 % of the paddy-growing area in the world is found in Asia, as rice is the staple food there. China and India, between them, have 80–90 % of the world's rice-growing areas.

Estimated CH_4 emissions from agricultural production activities have been steadily increasing since 1990. The increase in emissions from

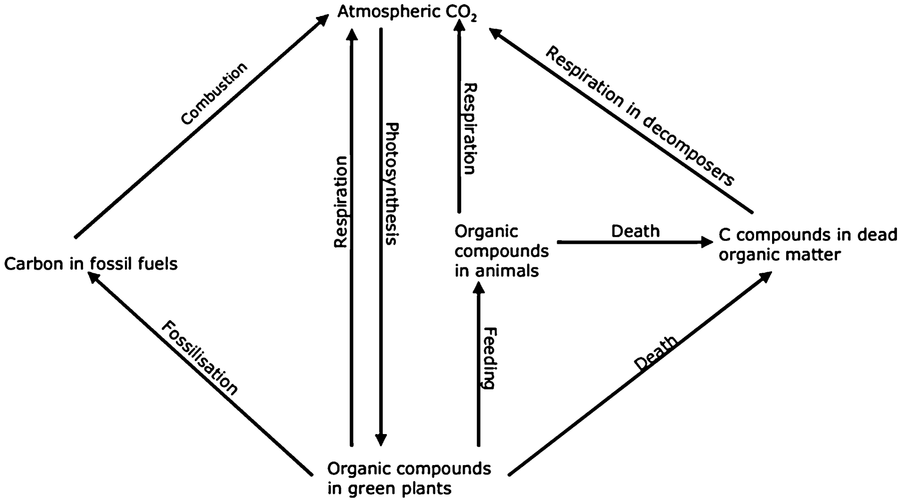

Fig. 2.5 The carbon cycle

enteric fermentation is attributed primarily to an increase in the cattle population, both beef and dairy cattle, and to increase in the swine population.

Methane is also emitted from landfills and other waste dumps. If the waste is put into an incinerator or burnt in the open, carbon dioxide is emitted. Methane is also emitted during the process of oil drilling, coal mining, and also from leaking gas pipelines (due to accidents and poor maintenance of sites).

Methane rose from a preindustrial atmospheric concentration of around 700 parts per billion by volume (ppbv) to about 1,789 ppbv by 2007.

Methane has 25 times the GWP of carbon dioxide and is therefore 25 CO_2e. It is released from the digestive systems of ruminant livestock by a process known as enteric fermentation and from manures and slurries. Similar to nitrous oxide, it is not possible to eliminate methane production from agriculture, but emissions can be reduced through improved livestock health, breed selection, and careful modifications to the diet and methods of manure storage and application. Increased production efficiency will mean that less methane is emitted per unit of production so careful management to optimize production will also help reduce emissions.

Ruminant animals (such as sheep and cattle) emit methane as a by-product of digesting feed. In 2008, this contributed 55 Mt of CO_2e to Australia's national Kyoto accounts, corresponding to 9.6 % of Australia's total greenhouse gas emissions and the largest component of agricultural emissions. The contribution is defined by the total number of animals and the emission rate per animal, which, in turn, is controlled by the animal's diet and management. Methane production by these animals represents lost energy that would otherwise be directed towards animal growth.

In ruminant animals, methane is produced as a by-product of the digestion of feed in the rumen under anaerobic condition. Methane emission is related to the composition of animal diet (grass, legume, grain, and concentrates) and the proportion of different feeds (e.g., soluble residue, hemicelluloses, and cellulose content). Mitigation of methane emitted from livestock is approached most effectively by strategies that reduce feed input per unit of product output. Nutritional, genetic, and management strategies to improve feed efficiency increase the rate of product (milk, meat) output per animal. Because most CH_4 is produced in the rumen by fermentation, practices that speed the passage of feed from the rumen can also reduce methane formation.

Methane is also formed in soil through the metabolic activities of a small but highly specific bacterial group called "methanogens." Their activity increases in the submerged, anaerobic conditions developed in the wetland rice fields, which limit the transport of oxygen into the soil, and the microbial activities render the water-saturated soil practically devoid of oxygen. The upland, aerobic soil does not produce methane. Water management, therefore, plays a major role in methane emission from soil. Altering water management practices, particularly mid-season aeration by short-term drainage as well as alternate wetting and drying, can greatly reduce methane emission from rice cultivation. Improving organic matter management by promoting aerobic degradation through composting or incorporating into soil during off-season drain period is another promising technique.

2.3.4 Nitrous Oxide (N_2O)

Nitrous oxide is a powerful greenhouse gas produced by soil cultivation practices, especially the use of commercial and organic fertilizers, fossil fuel combustion, nitric acid production, and biomass burning. Forests, grasslands, oceans, soils, nitrogenous fertilizers, and burning of biomass and fossil fuels are the sources of N_2O while it is removed by oxidation in the stratosphere. Soil with a contribution of about 65 % is the major contributor to the total N_2O emission. The main processes that cause emission of N_2O are soil cultivation, fertilizer and manure application, and burning of organic materials and fossil fuels. About 75 % of agricultural emissions of N_2O have been attributed to nitrogen fertilizer application to soils, including direct emissions from synthetic fertilizers, biological fixation in crops, and crop residues. This in turn depends on the type of fertilizer that is used, how and when it is used, and the methods of tilling that are followed. Contributions are also made by leguminous plants such as beans and pulses that add nitrogen to the soil. There are also indirect emissions attributed to soil leaching of N_2O and atmospheric deposition of nitrogenous compounds from agricultural activities.

A large amount of N_2O is also emitted from microbial denitrification of solid waste from livestock, primarily cattle. The amount released depends on the size of the animal, the amount of nitrogen in the waste, and the method of managing the waste.

Nitrous oxide has the capacity to absorb and reemit approximately 310 times the amount of heat compared to carbon dioxide – it has 310 times the global warming potential (GWP) of carbon dioxide. One kilogram of N_2O is therefore 310 kg CO_2e. Nitrous oxide is released during the production and use of manufactured fertilizers. The diagram below illustrates the chain of events in nitrogen cycling (Fig. 2.6).

Two chemical reactions in the soil produce N_2O. The process of nitrification can take place whereby microorganisms in the soil transform ammonium (NH_4+) to nitrate (NO_3-). N_2O is a by-product of nitrification. A second process, denitrification, involves the transformation of nitrate (NO_3-) (from the nitrification process or from the application of nitrate fertilizers) to nitrogen gas (N_2) and which N_2O is again a by-product.

Because nitrogen is such an important part of agricultural systems, the production of N_2O cannot be eliminated from farming systems. However, N_2O production (by nitrification and denitrification) needs to be controlled and reduced. This can be achieved through certain methods of manure and slurry application and storage, attention to accurate nutrient budgeting to achieve better nitrogen utilization in crop and grassland production systems, and attention to drainage and soil management. High N_2O emissions can occur when clover leys and other crop residues are plowed in if no growing crop is present to take up the nitrogen that is released, this again needs to be considered and managed carefully.

2.3.5 Chlorofluorocarbons (CFCs)

CFCs are synthetic compounds entirely of industrial origin used in a number of applications, but

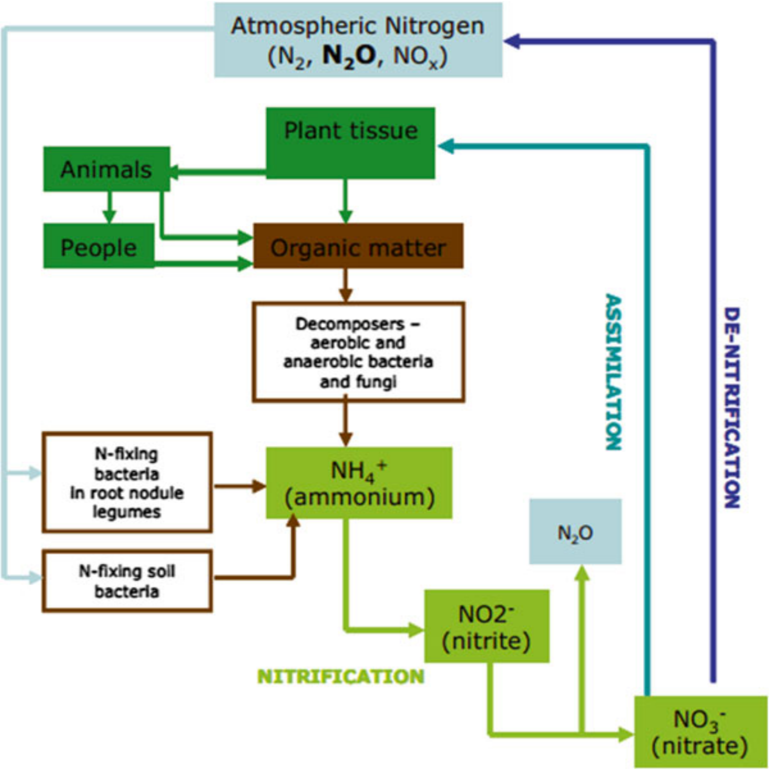

Fig. 2.6 The nitrogen cycle

now largely regulated in production and released to the atmosphere by international agreement are able to contribute to the destruction of the ozone layer. They are also greenhouse gases.

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3 Agriculture as a Source of GHGs

Abstract

Agricultural activities – the cultivation of crops and livestock for food – contribute to emissions in a variety of ways. Various management practices for agricultural soils can lead to production and emission of nitrous oxide (N_2O). Several activities that can contribute to N_2O emissions from agricultural lands range from fertilizer application to methods of irrigation and tillage. Management of agricultural soils accounts for over half of the emissions from the agriculture sector.

Livestock, especially cattle, produce methane (CH_4) as part of their digestion. This process is called enteric fermentation, and it represents almost one-third of the emissions from the agriculture sector.

The way in which manure from livestock is managed also contributes to CH_4 and N_2O emissions. Manure storage methods and the amount of exposure to oxygen and moisture can affect how these greenhouse gases are produced. Manure management accounts for about 13 % of the total greenhouse gas emissions from the agriculture sector in the United States.

Smaller sources of emissions include rice cultivation, which produces CH_4, and burning crop residues, which produce CH_4 and N_2O.

Keywords

Nitrous oxide • Methane • Fertilizer application • Enteric fermentation • Manure management • Rice cultivation • Burning crop residues

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Fig. 3.1 Main GHGs (CO_2, CH_4, and N_2O) released from agriculture (*o* oxygen, *h* hydrogen, *c* carbon, *n* nitrogen)

3.1 Global Agricultural Emissions

Agriculture is one of the main causes of the increase in greenhouse gases observed over the past 250 years (IPCC 2007). Agriculture contributes to greenhouse gas increases through land use in four main ways:

- CO_2 releases linked to deforestation.
- Methane releases from rice cultivation.
- Methane releases from enteric fermentation in cattle.
- Nitrous oxide releases from fertilizer application.

Agriculture releases to the atmosphere significant amounts of CO_2, CH_4, and N_2O (Fig. 3.1) (IPCC 2001). CO_2 is released largely from microbial decay or burning of plant litter and soil organic matter (Smith 2004). CH_4 is produced when organic materials decompose in oxygen-deprived conditions, notably from fermentative digestion by ruminant livestock, from stored manures, and from rice grown under flooded conditions (Mosier et al. 1998). N_2O is generated by the microbial transformation of nitrogen in soils and manures and is often enhanced where available nitrogen (N) exceeds plant requirements, especially under wet conditions (Oenema et al. 2005).

The atmospheric concentration of both methane (1,774 ppb) and nitrous oxide (319 ppb) has increased markedly world over as a result of human activities. The observed increase in concentrations of methane and nitrous oxide is predominantly due to agriculture and use of fossil fuel. Globally, agriculture contributes about 60 % of nitrous oxide and 50 % of methane emissions. Agricultural methane and nitrous oxide emissions increased by 17 % from 1990 to 2005 (Smith et al. 2007). The three major sources of global methane and nitrous oxide emissions from the agriculture sector are soil (38 % of CH_4+N_2O), rice production (11 % of CH_4), and biomass burning (12 % of CH_4+N_2O).

Table 3.1 Sources of direct and indirect agricultural GHGs

Sources of agricultural GHGs	CO_2e (million tons)
Methane from cattle enteric fermentation (CH_4)	1,792
Manures (CH_4+N_2O)	413
Nitrous oxide from fertilized soils (N_2O)	2,128
Fertilizer production (CO_2+N_2O)	410
Biomass burning (CH_4+N_2O)	672
Rice production (CH_4)	616
Farm machinery (seeding tilling, spraying, harvest) (CO_2)	158
Irrigation (CO_2)	369
Pesticide production	72
Land conversion to agriculture	5,900

Agriculture accounted for an estimated emission of 5.1–6.1 Gt CO_2e/year in 2005 (10–12 % of total global anthropogenic emissions of GHGs). CH_4 contributes 3.3 Gt CO_2e/year and N_2O 2.8 Gt CO_2e/year. Despite large annual exchanges of CO_2 between the atmosphere and agricultural lands, the net flux is estimated to be approximately balanced, with CO_2 emissions around 0.04 Gt CO_2/year only (low agreement, limited evidence). Together, these agricultural processes comprise 54 % of methane emissions, roughly 80 % of nitrous oxide emissions, and virtually all carbon dioxide emissions tied to land use (Table 3.1) (IPCC 2007).

In 2005, agriculture (crop and livestock) directly accounted for 13.5 % of global GHG emissions. Also, agriculture is a major driver of deforestation, which roughly accounts for an additional 17 % of global GHG emissions (IPCC 2007).

The main direct sources of GHG emissions in the agricultural sector are not only carbon dioxide (CO_2). Agriculture is a source of nitrous oxide (N_2O), accounting for 58 % of total emissions, mostly by soils and through the application of

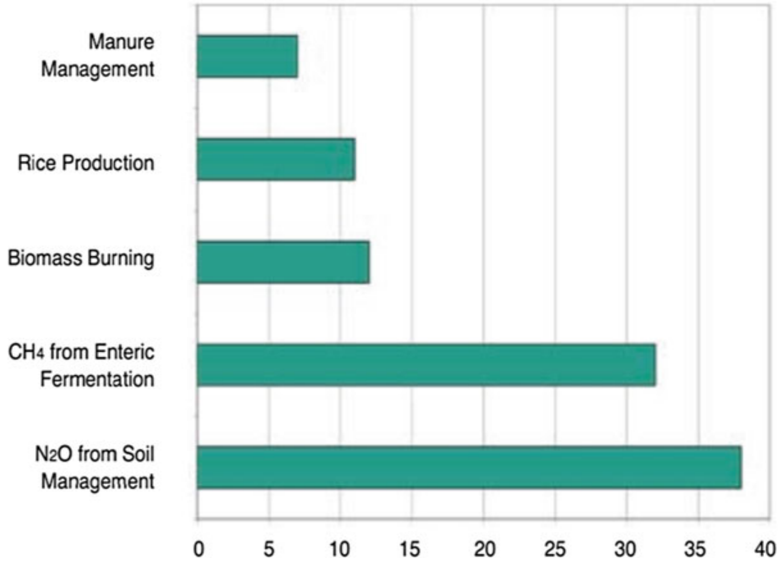

Fig. 3.2 GHG emissions in the agricultural sector (N_2O from soil management 38 %, CH_4 from enteric fermentation 32 %, biomass burning 12 %, rice production 11 %, manure management 7 %) (IPCC 2007; Smith et al. 2007)

fertilizers, and of methane (CH_4), accounting for 47 % of total emissions, essentially from livestock and rice cultivation.

As agricultural production is projected to increase in developing countries, so are agricultural emissions. IPCC estimates that N_2O emissions will increase by 35–60 % by 2030 and CH_4 by 60 % (IPCC 2007). The IPCC also projects additional land being converted to agriculture.

Major agricultural activities which contribute to elevated GHG emissions include:

- Agricultural soil management covers a broad array of practices including fertilization with synthetic fertilizer and animal manures; manure deposition by grazing animals, soil cultivation; production on N fixing crops and forages; irrigation; and other practices. The category covers GHG emissions from both cropland and grasslands.
- Enteric fermentation is primarily CH_4 produced by the digestive processes of agricultural animals which are emitted from the animals as gas.
- Manure management emissions are CH_4 and N_2O released from manure during storage and handling.
- Rice cultivation done under anaerobic conditions in flooded fields results in CH_4 emissions.
- Field burning of agricultural residues results mostly in CO_2 emissions, which are not counted because it is assumed that CO_2 will be reabsorbed by plants in the next growing season. Field burning, however, also results in release of CH_4, N_2O, and other minor GHGs.

Agriculture accounts for roughly 14 % of the total global GHG emissions or about 6.8 Gt of CO_2e/year (Fig. 3.2) (IPCC 2007). In the period since 1990, total provincial GHG emissions have risen, while agricultural GHG emissions have remained essentially constant. Within agriculture, the main sources responsible for GHG emissions are ruminant livestock belching and manure, both of which release CH_4 into the air, and release of N_2O from soils as a result of application of synthetic nitrogen fertilizers and manure. In addition, there are indirect GHG emissions from agricultural activities, such as the CO_2 emitted during fossil fuel combustion by farm machinery and the manufacture of fertilizers and farm machinery. These types of emissions are typically reported by the transportation and manufacturing sectors. The main greenhouse gases emitted by the agriculture sector are N_2O, CH_4, and CO_2. Since 1990, GHG emissions from agricultural soils and enteric fermentation have decreased slightly, while emissions from manure have increased slightly. The overall impact has remained the same.

In 2008, agricultural soils contributed 15 Mt CO_2e, principally from N_2O emissions associated with the use of fertilizers. Emissions of N_2O from soils under cropping systems occur principally when excess inorganic nitrogen is present in the form of nitrate. High soil nitrogen levels, particularly under wet soil conditions, are a significant driver of greenhouse gas emissions associated with fertilizer use.

3.2 Emissions by Agricultural Source

Most of the (about 74 % of total) greenhouse gas emissions originate in industrialized countries. Emissions from rice production and burning of biomass were heavily concentrated in the group of developing countries, with 97 % and 92 % of world totals, respectively. While CH_4 emissions from rice occurred mostly in South and East Asia, where it is a dominant food source (82 % of total emissions), those from biomass burning originated in Sub-Saharan Africa and Latin America and the Caribbean (74 % of total). Manure management was the only source for which emissions were higher in the group of developed regions (52 %) than in developing regions (48 %) (Fig. 3.3) (US-EPA 2006b).

Globally, agricultural CH_4 and N_2O emissions have increased by nearly 17 % from 1990 to 2005, an average annual emission increase of about 60 Mt CO_2e/year. During that period, the five regions composed of Non-Annex I countries showed a 32 % increase and were, by 2005, responsible for about three-quarters of total agricultural emissions. The other five regions, mostly Annex I countries, collectively showed a decrease of 12 % in the emissions of these gases (high agreement, much evidence).

Further improvements in productivity will require higher use of irrigation and fertilizer, increasing the energy demand for moving water and manufacturing fertilizer (Schlesinger 1999). Also, irrigation and N fertilization can increase GHG emissions (Mosier 2001).

Growing demand for meat may induce further changes in land use (e.g., from forestland to grassland), often increasing CO_2 emissions and increased demand for animal feeds (e.g., cereals). Larger herds of beef cattle will cause increased emissions of CH_4 and N_2O, although use of intensive systems (with lower emissions per unit product) is expected to increase faster than growth in grazing-based systems. This

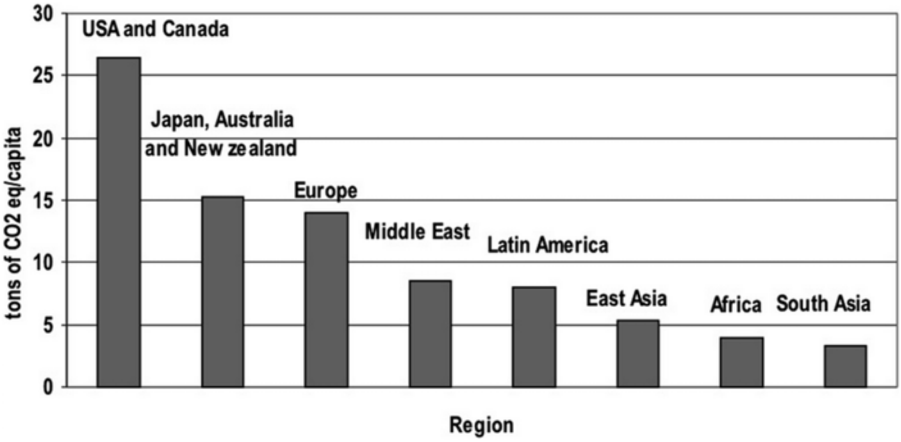

Fig. 3.3 Greenhouse gas emissions from different countries

may attenuate the expected rise in GHG emissions.

Intensive production of beef, poultry, and pork is increasingly common, leading to increases in manure with consequent increases in GHG emissions. This is particularly true in the developing regions of South and East Asia, and Latin America, as well as in North America.

Changes in policies (e.g., subsidies) and regional patterns of production and demand are causing an increase in international trade of agricultural products. This is expected to increase CO_2 emissions, due to greater use of energy for transportation.

3.2.1 Land Use Change

Land use and land-use changes can significantly contribute to overall climate change. Vegetation and soils typically act as a carbon sink, storing carbon dioxide that is absorbed through photosynthesis. When the land is disturbed, the stored carbon dioxide along with methane and nitrous oxide are emitted, reentering the atmosphere. The clearing of land can result in soil degradation, erosion, and the leaching of nutrients, which can also possibly reduce its ability to act as a carbon sink. This reduction in the ability to store carbon can result in additional carbon dioxide remaining in the atmosphere, thereby increasing the total amount of greenhouse gases.

There are two types of land-use change: direct anthropogenic (human-caused) changes and indirect changes. Examples of anthropogenic changes include deforestation, reforestation and afforestation, and agriculture. Indirect changes include those changes in climate or in carbon dioxide concentrations that force changes in vegetation. On a global scale, carbon dioxide emissions from land-use changes represent an estimated 18 % of total annual emissions; one-third of that from developing countries and over 60 % from the lesser developing countries.

3.2.1.1 Direct Anthropogenic Changes

The effect of land use on the climate primarily depends on the type of land cover present within an area. For example, if rainforest is removed and replaced by crops, there will be less transpiration (evaporation of water from leaves) leading to warmer temperatures in that area. On the other hand, if irrigation is used on farmland, more water is transpired and evaporated from moist soils, which cools and moistens the atmosphere. The additional transpiration can also affect levels of precipitation and cloudiness in an area.

In regions with heavy snowfall, reforestation or afforestation would cause the land to reflect less sunlight, resulting in the absorption of more heat on the land. This would, in turn, result in a net warming effect despite the removal of carbon dioxide from the atmosphere through the process of photosynthesis during the growing season. Additional reforestation could increase transpiration, leading to more water vapor in the air. In the troposphere, water vapor is considered to be the biggest greenhouse gas contributor to global warming.

3.2.1.2 Indirect Changes

The main ways that changes in climate can alter land use is through higher mean annual temperatures, altered precipitation patterns, and more frequent and extreme weather events. The territories of many plant species depend largely on temperature and rainfall patterns. As climate change affects these patterns, many types of trees and vegetation are forced to shift to higher altitudes and latitudes. While greater variability in rainfall patterns can decrease overall plant growth, higher temperatures can extend growing seasons, possibly allowing for more than one cropping cycle during the same season or the expansion of agricultural land toward the higher elevations.

3.2.2 Agricultural Soils (N_2O)

N_2O is produced naturally in soils through the microbial process of denitrification and nitrification. A number of anthropogenic activities add nitrogen to the soils, thereby increasing the amount of nitrogen available for nitrification and denitrification and ultimately the amount of N_2O emitted (US-EPA 2011).

Table 3.2 Greenhouse gas emissions from agriculture

Type of emission	Total emissions 1990 ($MtCO_2e$)	Total emissions 2005 ($MtCO_2e$)	Total emissions 2030 (projection) ($MtCO_2e$)
Agricultural soils (N_2O)	1,804 (30.5 %)	1,984 (32.5 %)	2,666 (36.5 %)
Enteric fermentation (CH_4)	1,755 (29.6 %)	1,864 (30.5 %)	2,289 (31.3 %)
Rice cultivation (CH_4)	670 (11.3 %)	710 (11.6 %)	739 (10.1 %)
Manure management (CH_4, N_2O)	408 (6.9 %)	389 (6.4 %)	455 (6.2 %)
Other emissions (CH_4, N_2O)	1,283 (21.7 %)	1,164 (19.0 %)	1,164 (15.9 %)
Total non-CO_2 emissions	5,920 (100 %)	6,111 (100 %)	7,313 (100 %)

- Between 1990 and 2005, N_2O emissions from agricultural soil management have increased 10 %, from 1,804 to 1,984 $MtCO_2e$, which corresponds to 32.5 % of total agricultural emissions (Table 3.2).
- Underlying this trend are increases in crop production and fertilizer use and other nitrogen sources such as crop residues.
- From 2005 to 2030, N_2O emissions from agricultural soils are projected to increase 34 %, from 1,984 to 2,666 $MtCO_2e$. This projection assumes continued increases in fertilizer usage. Over the projection period, emissions are expected to increase in all regions (US-EPA 2011).

3.2.2.1 Inventory of Nitrous Oxide Emissions from Managed Soils

Nitrous oxide is produced naturally in soils through the processes of nitrification and denitrification. Nitrification is the aerobic microbial oxidation of ammonium to nitrate, and denitrification is the anaerobic microbial reduction of nitrate to nitrogen gas (N_2). Nitrous oxide is a gaseous intermediate in the reaction sequence of denitrification and a by-product of nitrification that leaks from microbial cells into the soil and ultimately into the atmosphere. One of the main controlling factors in this reaction is the availability of inorganic N in the soil. This methodology, therefore, estimates N_2O emissions using human-induced net N additions to soils (e.g., synthetic or organic fertilizers, deposited manure, crop residues, sewage sludge) or of mineralization of N in soil organic matter following drainage/management of organic soils or cultivation/land-use change on mineral soils.

The emissions of N_2O that result from anthropogenic N inputs or N mineralization occur through both (a) direct pathway (i.e., directly from the soils to which the N is added/released) and (b) indirect pathways: (1) following volatilization of NH_3 and NOx from managed soils and from fossil fuel combustion and biomass burning and the subsequent redeposition of these gases and their products NH_4^+ and NO_3^- to soils and waters and (2) after leaching and runoff of N, mainly as NO_3^-, from managed soils.

In most soils, an increase in available N enhances nitrification and denitrification rates which then increase the production of N_2O. Increases in available N can occur through human-induced N additions or change of land-use and/or management practices that mineralize soil organic N.

3.2.3 Enteric Fermentation (CH_4)

Normal digestive processes in animals result in CH_4 emissions. Enteric fermentation refers to a fermentation process whereby microbes in an animal's digestive system ferment food. CH_4 is produced as a by-product and can be exhaled by the animal. Domesticated ruminants such as cattle, buffalo, sheep, goats, and camels account for the majority of CH_4 emissions in this sector (US-EPA 2011).

- Global CH_4 emissions from enteric fermentation increased by 6 % between 1990 and 2005, from 1,755 to 1,864 $MtCO_2e$, corresponding to 30.5 % of total agricultural emissions (Table 3.2).
- From 2005 to 2030, CH_4 emissions from enteric fermentation are projected to increase 23 %, from 1,864 to 2,289 $MtCO_2e$ (US-EPA 2011).

Table 3.3 Methane emission coefficients from different rice ecosystems in the year 2000

Ecosystem	Water regime[a]	Rice area (M ha)	Emission coefficient (kg ha^{-1})	Methane emission (Gg)
Irrigated	CF	6.85	162	1,138
	SA	8.99	66	605
	MA	9.49	18	144
Rainfed	DP	8.66	66	550
	FP	4.35	190	827
Deep water	DW	1.37	160	217
Upland		4.8	0	0
Total		44.7		3,483

[a] *CF* continuously flooded, *SA* single aeration, *MA* multiple aeration, *DP* drought prone, *FP* flood prone, *DW* deep water

3.2.4 Rice Cultivation (CH_4)

The anaerobic decomposition of organic matter in flooded rice fields produces CH_4. When fields are flooded, aerobic decomposition of organic material gradually depletes the oxygen present in the soil and flood water, causing anaerobic conditions in the soil to develop. Once the environment becomes anaerobic, CH_4 is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. Several factors influence the amount of CH_4 produced, including water management practices and the quantity of organic material available to decompose (US-EPA 2011).

- CH_4 emissions from rice production have increased 6 % between 1990 and 2005, from 670 to 710 $MtCO_2e$, corresponding to 11.6 % of total agricultural emissions. Underlying this trend has been a similar increase in the land area of harvested rice (Table 3.2).
- From 2005 to 2030, CH_4 emissions from this source are projected to increase 4 % from 710 to 739 $MtCO_2e$ (this projection assumes a further increase in rice area harvested over the projection period) (US-EPA 2011).

3.2.4.1 Inventory of Methane Emission from Rice Fields

Rice fields with anaerobic conditions in wetlands as a result of soil submergence under water are one of the major sources of methane emission. Decomposition of organic material in flooded rice fields produces methane (CH_4), which escapes into the atmosphere primarily by vascular transport through the rice plants. The volume of CH_4 emitted from a given area of rice is a function of the crop duration, water regimes, and organic soil amendments. The CH_4 emissions are estimated by multiplying the seasonal emission factors by the annual harvested area. Harvested area for each subunit (state) on multiplication with the respective emission factor is the representative of conditions that define the subunit (state). The total annual emissions are equal to the sum of emissions from each subunit of harvested area (Table 3.3).

3.2.5 Manure Management (CH_4, N_2O)

Manure management produces CH_4 and N_2O. CH_4 is produced during the anaerobic decomposition of manure, while N_2O is produced by the nitrification and denitrification of the organic nitrogen content in livestock manure and urine (US-EPA 2011).

- Between 1990 and 2005, CH_4 and N_2O emissions from manure management decreased by 5 %, from 408 to 389 $MtCO_2e$, corresponding to 6.4 % of total agricultural emissions (Table 3.2).
- From 2005 to 2030, global CH_4 and N_2O emissions from manure management are projected to increase by 17 %, from 389 to 455 $MtCO_2e$ (US-EPA 2011).

3.2.6 Other Agriculture Sources of Non-CO_2 Emissions (CH_4, N_2O)

This category includes emission sources from the agricultural sector that are relatively small compared to the sector overall. The data presented include the following sources of CH_4 and N_2O: agricultural soils (CH_4), field burning of agricultural residues (CH_4, N_2O), prescribed burning of savannas (CH_4, N_2O), and open burning from forest clearing (CH_4).

- Between 1990 and 2005, total emissions from other agricultural sources decreased from 1,283 to 1,164 $MtCO_2e$ (US-EPA 2011), corresponding to 19 % of total agricultural emissions (Table 3.2).

3.2.7 Deforestation Emissions

Agriculture is the leading cause of some 75 % of global deforestation. If rates of deforestation continues as projected, forests will diminish dramatically by 2100 (Strassburg et al. 2012).

- Deforestation and land-use change (the conversion of forests into farmland) account for 2,200–6,600 million metric tons of carbon dioxide equivalent (Mt CO_2e) per year or 30–50 % of agricultural emissions and about 4–14 % of global emissions (Vermeulen et al. 2012).
- Since 1850, land-use change directly contributed some 35 % of human-generated CO_2 emissions (Foley et al. 2005).
- Past trends imply that ~10 million km^2 of land will be cleared by 2050 to meet demand, leading to annual emissions of 3,000 $MtCO_2e$ per year. A future course that spares more land could reduce land clearing to ~2 million km^2 and GHG emissions to 1,000 $MtCO_2e$/year per year (Tilman et al. 2001).
- In the 1980s and 1990s, rainforests were the primary source of new agricultural land in the tropics. Future expansion of the global agricultural land base will clear tropical forests and shrub land ecosystems (Gibbs et al. 2010).
- The combined contribution of deforestation and forest degradation emissions to total human-generated CO_2 emissions is about 12 % (with a range of 6–18 %) (Van der Werf et al. 2009).
- Between 1980 and 2000, more than 55 % of new agricultural land replaced intact forests; another 28 % replaced degraded forests. Even with agricultural yield increases and intensification, net agricultural area expansion will probably be needed to meet future demand (Gibbs et al. 2010).
- Land-use activities, primarily the expansion of agricultural land and the extraction of timber, have caused a net loss of ~7 to 11 million km^2 of forest in the past 300 years (Foley et al. 2005).
- Forests cover about 3,952 million hectares of the globe – about 30 % of the world's land area. From 2000 to 2005, gross deforestation continued at a rate of 12.9 million hectares per year. Due to afforestation, landscape restoration, and the natural expansion of forests, the most recent estimate of net forest loss is 7.3 million hectares per year (IPCC 2007).
- Croplands and pastures have become one of the largest terrestrial biomes on the planet, occupying ~40 % of the land surface and rivaling forest cover in extent (Foley et al. 2005).
- Between 1963 and 2005, the global area of cropland harvested increased 30 % from 8.4 million km^2 to 11.0 million km^2.
- Managed grazing occupies 25 % of the global land surface (more than 33 million km^2), making it the planet's single most extensive form of land use (Asner et al. 2004).
- Land use for the livestock sector spans more than 39 million km^2 (~30 % of the world's surface land area). Of this, 5 million km^2 is crops, most of which are intensively managed; 14 million km^2 is pasture with relatively high productivity; and 20 million km^2 is extensive pastures with relatively low productivity (FAO 2006).
- Some irrigated lands have become heavily salinized, causing a worldwide loss of ~1.5 million hectares of arable land per year and an estimated US$ 11 billion in lost production (Foley et al. 2005).

- Soil erosion, reduced fertility, or overgrazing impacts up to ~40 % of global croplands (Foley et al. 2005).
- The main driver of land-use change for agriculture was population growth. Now, in most regions, it's shifting to dietary change (Kastner et al. 2012).
- Cropland would have to be nearly doubled if the projected global population of more than 9 billion people in 2050 were to have North America's current diet and agricultural technology. Cropland would have to be expanded 70 % if the global population had Western Europe's diet and technology (Kastner et al. 2012).

3.2.8 Emissions from Production of Biofuels

When compared to fossil fuels, manufactured liquid biofuels do not necessarily produce fewer greenhouse gas emissions.

- The two key factors that determine whether biofuels lead to lower or higher greenhouse gas emissions than fossil fuels are:
  - How the biomass (the basis of the biofuel) is produced and harvested. This process could emit carbon through, for example, fertilizers and machinery.
  - Where the biomass is produced. Biofuel production that leads directly or indirectly to land-use change emits high levels of carbon.
- The ethanol produced from a hectare of maize reduces greenhouse gas emissions by 1.8 tons of carbon dioxide equivalent ($MtCO_2e$) per hectare per year compared to the oil equivalent. But each hectare of forest, grasslands, or savannahs converted to cropland emits greenhouse gases when the carbon-storing biomass that makes up these biomes is cut down. For forests, these "up-front" emissions are 604–1,146 $MtCO_2e$ per hectare depending on forest type and maturity; for grasslands or savannahs, these emissions are 75–305 $MtCO_2e$ (Searchinger et al. 2008).
- Some liquid biofuel policy alternatives could significantly increase global fertilizer use to satisfy additional production needs. Additional greenhouse gas emissions due to increased fertilizer use (primarily N_2O) could be greater than those arising from land-use change (Mosnier et al. 2012).
- Using good cropland to expand (liquid) biofuel production will likely exacerbate global warming the same way as directly converting forest and grasslands (Searchinger et al. 2008). For example, increasing ethanol production by 56 billion liters, which uses the equivalent of 12.8 million hectares of maize in the United States, would require bringing an additional 10.8 million hectares of land into cultivation to meet demand for maize for other uses (Searchinger et al. 2008).
- The Organization for Economic Co-operation and Development (OECD) and the United Nations Food and Agriculture Organization (FAO 2012) project that from 2012 to 2021, global ethanol and biodiesel production will expand from 113 billion to 180 billion liters annually. The largest markets – the United States, Brazil, and the European Union – will grow at a slower pace than in recent years (USDA 2011).
- From 2012 to 2021, ethanol prices are expected to increase from US$ 0.85 to 0.95 per liter, while biodiesel prices are expected to increase from US$ 1.53 to 1.81 per liter.
- Continued expansion is largely due to biofuel policies, primary among them use mandates and tax incentives (USDA 2011), and high crude oil prices.

3.2.9 Biomass Burning

Burning of crop residues in fields is practiced for clearing the land rapidly and inexpensively and allowing the tillage practices to proceed unimpeded by the residual crop material during preparations for the next growing season. The crops whose residues are normally burnt in India and in many other countries are rice, wheat, cotton, maize, millet, sugarcane, jute, pulses, rapeseed–mustard, and groundnut. On burning, the crop residues are converted into gases such as carbon dioxide, methane, nitrous oxide, SOx, NOx, CO, soot and particulate matter, ash, aerosols, light hydrocarbons, volatile organic compounds (VOCs) such as benzene, and semi-volatile organic compounds (SVOCs) including polycyclic aromatic hydrocarbons (PAHs). The composition of the gases depends upon the burning conditions. Burning takes place in two phases: flaming and smoldering. During the flaming phase, concentration of carbon dioxide is more, whereas in the smoldering phase, concentration of carbon monoxide is more.

3.3 Emission Trends (Global and Regional)

3.3.1 Key Messages

- Greenhouse gases (GHGs) influence the earth's climate because they interact with flows of heat energy in the atmosphere.
- The main GHGs influenced directly by human activities are carbon dioxide (CO_2), methane, nitrous oxide, ozone, and synthetic gases. Water vapor, although an important GHG, is not influenced directly by human activities.
- The amount of warming produced by a given rise in GHG concentrations depends on "feedback" processes in the climate system, which can either amplify or dampen a change. The net effect of all climate feedbacks is to amplify the warming caused by increasing CO_2 and other GHGs of human origin.
- The atmospheric level of CO_2 (the most important GHG influenced by human activities) rose from about 280 ppm in 1800 to 386 ppm in 2009 and is currently increasing at nearly 2 ppm per year.
- CO_2 levels are rising mainly because of the burning of fossil fuels and deforestation. Over half of this CO_2 input to the atmosphere is offset by natural CO_2 "sinks" in the land and oceans, which constitute a massive natural ecosystem service helping to mitigate humanity's emissions.
- To have a 50:50 chance of keeping human-induced average global warming below 2 °C, it will be necessary to stop almost all CO_2 emissions before cumulative emissions reach one trillion tons of carbon. The world has already emitted more than half of this quota since the industrial revolution, and (at current growth rates for CO_2 emissions) the rest will be emitted by the middle of this century.
- Climate change is a risk management issue – the longer we take to act and the weaker our actions, the greater the risk of dangerous outcomes.

3.3.2 Food System Emissions

Food system emissions – from production to consumption – contribute 9,800–16,900 million metric tons of carbon dioxide equivalent ($MtCO_2e$) per year, or 19–29 % of total greenhouse gas emissions (Vermeulen et al. 2012).

- Food production and consumption contribute 19–29 % of total greenhouse gas emissions to 9,800–16,900 $MtCO_2e$ (million metric tons of carbon dioxide equivalent at 2008 levels) per year. This figure includes the full supply chain, including fertilizer manufacture, agriculture, processing, transport, retail, household food management, and waste disposal.
- Agriculture makes the greatest contribution to total food system emissions. It contributes 7,300–12,700 $MtCO_2e$ per year – equivalent to 80–86 % of food systems emissions and 14–24 % of total global emissions (Vermeulen et al. 2012).
- Deforestation and land-use change account for 2,200–6,600 $MtCO_2e$ per year to 30–50 % of agricultural emissions and 4–14 % to total global emissions.
- Direct emissions from agriculture, through, for example, activities like managing soils, crops, and livestock, contribute 5,100–6,100 $MtCO_2e$ per year to 50–70 % of agricultural emissions and 10–12 % to total global emissions.
- The food chain, excluding agriculture, contributes 14–20 % of food-related emissions and, at most, 5 % of global emissions.
- The proportion of emissions from portions of the food chain that take place after food leaves

the farm ("post-farm gate") is larger in high-income countries. For example, these activities make up some 50 % of food system emissions in the United Kingdom (Garnett 2011). Middle-income countries will likely follow this trend in the future.

- Fisheries and aquaculture are estimated to make only minor contributions to greenhouse gas emissions.

3.3.3 Livestock Emissions

The livestock sector is a major contributor to climate change, generating significant emissions of CO_2, CH_4, and N_2O. Livestock contribute to climate change by emitting GHGs either directly (e.g., from enteric fermentation and manure management) or indirectly (e.g., from feed-production activities, conversion of forest into pasture). Based on a life cycle assessment (LCA), it is estimated that the sector emits about 7.1 gigatons of CO_2e, about 18 % of the total anthropogenic GHG emissions (FAO 2006).

On a global scale, the emission intensity of meat and milk, measured by output weight, corresponds on average to 46.2 kgCO_2e per kg of carcass weight (CW), 6.1 kg CO_2e/kg CW, and 5.4 kg CO_2e/kg CW for beef, pork, and chicken meat, respectively, and 2.8 kgCO_2e/kg of milk (FAO 2013). There is significant variability in emissions across the different regions. Emissions from Europe and North America range between 1.6 and 1.9 kgCO_2e/kg fat- and protein-corrected milk (FPCM) at the farm gate. The highest emissions are estimated for sub-Saharan Africa with an average of 9.0 kgCO_2e/kg FPCM at the farm gate. GHG emissions for Latin America and the Caribbean, Near East and North Africa, and South Asia range between 3 and 5 kgCO_2e/kg FPCM at the farm gate. The global average is estimated at 2.8 kg CO_2e (FAO 2013).

GHG emissions are inversely related to productivity. At very low levels of milk production (200 kg per cow per year), emissions were found to be 12 kgCO_2e/kg FPCM compared to 1.1 kgCO_2e/kg FPCM for high production levels (about 8,000 kg of milk) (Gerber et al. 2011).

The global livestock sector emits almost 6,000 million metric tons of carbon dioxide equivalents (MtCO_2e) per year at 2008 levels and accounts for about 11 % of global greenhouse gas emissions. Emissions from the sector are expected to increase 70 % by 2050 (PBL 2009).

- Animal protein from monogastric animals (largely pigs and poultry) is more efficient in terms of grams of protein per unit of greenhouse gas emissions than animal protein from ruminants (cattle, sheep, and goats). However, this simplistic comparison does not take into account key issues such as the suitability of land for pasture or feed production, nutritional value beyond protein, or the use of by-products (Garnett 2009). Roughly one-third of livestock emissions come from land use and land-use changes.
- Indirect emissions from the clearing of forests due to the encroachment of grazing into forested areas as well as from the cultivation of feed crops play an important role in the total agricultural greenhouse gas emissions.
- FAO (2006) calculates that globally, livestock-induced land-use change generates 2,400 MtCO_2e a year, or approximately 4–5 % of global greenhouse gas emissions.
- The PBL report (2009) gives a slightly different number, attributing about 2,200 MtCO_2e per year to land use and livestock-induced land-use change.
- If CH_4 emissions grow in direct proportion to increases in livestock numbers, then global livestock-related methane production is expected to increase by 60 % by 2030. However, changes in feeding practices and manure management could lessen this increase (Smith et al. 2007).
- Emissions from livestock are highest per capita in high-income countries, with estimates ranging up to 31 % of total emissions in the European Union. On the other hand, emissions may be higher per animal in low-income countries (Garnett 2009).

3.3.4 Direct Agricultural Emissions

Non-CO_2 agricultural emissions are about 6,100 $MtCO_2e$ per year – about 11 % of total global greenhouse gas emissions and 56 % of global non-CO_2 greenhouse gas emissions (US-EPA 2011).

- Non-CO_2 agricultural emissions are primarily N_2O from soil management, including the application of inorganic and organic fertilizers, and methane (CH_4) from rice production and farm animal digestion.
- Agriculture's responsibility for non-CO_2 greenhouse gas emissions is expected to grow about 20 % by 2030, reaching 7,313 $MtCO_2e$ per year.

With an estimated global emission of non-CO_2 GHGs from agriculture between 5,120 $MtCO_2e$/year (Denman et al. 2007) and 6,116 $MtCO_2e$/year (US-EPA 2006a) in 2005, agriculture accounts for 10–12 % of total global anthropogenic emissions of GHGs. Agriculture contributes about 47 % and 58 % of total anthropogenic emissions of CH_4 and N_2O, respectively, with a wide range of uncertainty in the estimates of both the agricultural contribution and the anthropogenic total. N_2O emissions from soils and CH_4 from enteric fermentation constitute the largest sources, 38 % and 32 % of total non-CO_2 emissions from agriculture in 2005, respectively (US-EPA 2006a). Biomass burning (12 %), rice production (11 %), and manure management (7 %) account for the rest. CO_2 emissions from agricultural soils are not normally estimated separately, but are included in the land use, land-use change, and forestry sector (e.g., in national GHG inventories) (Fig. 3.4). So there are few comparable estimates of emissions of this gas in agriculture. Agricultural lands generate very large CO_2 fluxes both to and from the atmosphere (IPCC 2001), but the net flux is small. US-EPA (2006b) estimated a net CO_2 emission of 40 $MtCO_2e$ from agricultural soils in 2000, less than 1 % of global anthropogenic CO_2 emissions.

Both the magnitude of the emissions and the relative importance of the different sources vary widely among world regions. In 2005, the group of five regions mostly consisting of Non-Annex I countries was responsible for 74 % of total agricultural emissions.

In seven of the ten regions, N_2O from soils was the main source of GHGs in the agricultural sector in 2005, mainly associated with N fertilizers and manure applied to soils. In the other three regions – Latin America and the Caribbean; the countries of Eastern Europe, the Caucasus, and Central Asia; and OECD Pacific – CH_4 from enteric fermentation was the dominant source (US-EPA 2006a). This is due to the large livestock population in these three regions which, in 2004, had a combined stock of cattle and sheep equivalent to 36 % and 24 % of world totals, respectively (FAO 2003).

3.3.5 Trends Since 1990

Globally, agricultural CH_4 and N_2O emissions increased by 17 % from 1990 to 2005, an average annual emission increase of 58 MtCO2e/year (US-EPA 2006a). Both gases had about the same share of this increase. Three sources together explained 88 % of the increase: biomass burning (N_2O and CH_4), enteric fermentation (CH_4), and soil N_2O emissions (US-EPA 2006a).

During that period, according to US-EPA (2006a), the five regions composed of Non-Annex I countries showed a 32 % increase in non-CO_2 emissions (equivalent to 73 $MtCO_2e$/year). The other five regions, with mostly Annex I countries, collectively showed a decrease of 12 % (equivalent to 15 $MtCO_2e$/year) (Fig. 3.4). This was mostly due to non-climate macroeconomic policies in the Central and Eastern European and the countries of Eastern Europe, the Caucasus, and Central Asia.

3.3.6 Future Global Trends

Agricultural N_2O emissions are projected to increase by 35–60 % up to 2030 due to increased nitrogen fertilizer use and increased animal manure production (FAO 2003). Similarly, US-EPA (2006a) (Fig. 3.4) estimated that N_2O emissions will increase by about 50 % by 2020

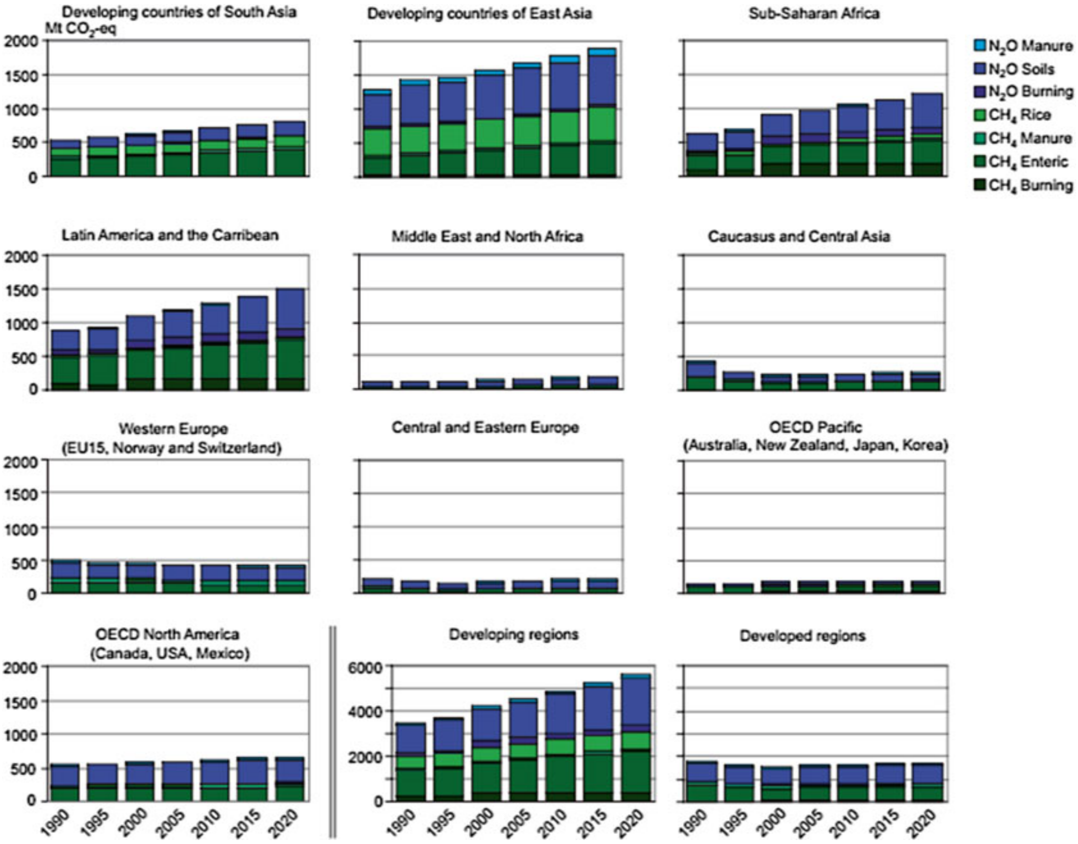

Fig. 3.4 Estimated historical and projected N_2O and CH_4 emissions in the agricultural sector of the ten world regions during the period 1990–2020 (US-EPA 2006a)

(relative to 1990). If demands for food increase, and diets shift as projected, then annual emissions of GHGs from agriculture may escalate further. But improved management practices and emerging technologies may permit a reduction in emissions per unit of food (or protein) produced and perhaps also a reduction in emissions per capita food consumption.

If CH_4 emissions grow in direct proportion to increases in livestock numbers, then global livestock-related methane production is expected to increase by 60 % up to 2030 (FAO 2003). However, changes in feeding practices and manure management could ameliorate this increase. US-EPA (2006a) forecast that combined methane emissions from enteric fermentation and manure management will increase by 21 % between 2005 and 2020.

The area of rice grown globally is forecasted to increase by 4.5 % to 2030 (FAO 2003), so methane emissions from rice production would not be expected to increase substantially. There may even be reductions if less rice is grown under continuous flooding (causing anaerobic soil conditions) as a result of scarcity of water or if new rice cultivars that emit less methane are developed and adopted (Wang et al. 1997). However, US-EPA (2006a) projects a 16 % increase in CH_4 emissions from rice crops between 2005 and 2020, mostly due to a sustained increase in the area of irrigated rice.

No baseline agricultural non-CO_2 GHG emission estimates for the year 2030 have been published, but according to US-EPA (2006a), aggregate emissions are projected to increase by ~13 % during the decades 2000–2010 and

2010–2020. Assuming similar rates of increase (10–15 %) for 2020–2030, agricultural emissions might be expected to rise to 8,000–8,400, with a mean of 8,300 $MtCO_2e$ by 2030. The future evolution of CO_2 emissions from agriculture is uncertain. Due to stable or declining deforestation rates (FAO 2003), and increased adoption of conservation tillage practices (FAO 2001), these emissions are likely to decrease or remain at low levels.

3.3.7 Regional Trends

The Middle East and North Africa, and Sub-Saharan Africa have the highest projected growth in emissions, with a combined 95 % increase in the period 1990 to 2020 (US-EPA 2006a). Sub-Saharan Africa is the one world region where per capita food production is either in decline or roughly constant at a level that is less than adequate (Scholes and Biggs 2004). This trend is linked to low and declining soil fertility (Sanchez 2002) and inadequate fertilizer inputs. Although slow, the rising wealth of urban populations is likely to increase demand for livestock products. This would result in intensification of agriculture and expansion to still largely unexploited areas, particularly in South and Central Africa (including Angola, Zambia, DRC, Mozambique, and Tanzania), with a consequent increase in GHG emissions.

East Asia is projected to show large increases in GHG emissions from animal sources. According to FAO (FAOSTAT 2006), total production of meat and milk in Asian developing countries increased more than 12 times and 4 times, respectively, from 2004 to 1961. Since the per capita consumption of meat and milk is still much lower in these countries than in developed countries, increasing trends are expected to continue for a relatively long time. Accordingly, US-EPA (2006b) forecast increases of 153 % and 86 % in emissions from enteric fermentation and manure management, respectively, from 1990 to 2020. In South Asia, emissions are increasing mostly because of expanding use of N fertilizers and manure to meet demands for food, resulting from rapid population growth.

In Latin America and the Caribbean, agricultural products are the main source of exports. Significant changes in land use and management have occurred, with forest conversion to cropland and grassland being the most significant, resulting in increased GHG emissions from soils (CO_2 and N_2O). The cattle population has increased linearly from 176 to 379 Mhead between 1961 and 2004, partly offset by a decrease in the sheep population from 125 to 80 Mhead. All other livestock categories have increased in the order of 30–600 % since 1961. Cropland areas, including rice and soybean, and the use of N fertilizers have also shown dramatic increases (FAOSTAT 2006). Another major trend in the region is the increased adoption of no-till agriculture, particularly in the Mercosur area (Brazil, Argentina, Paraguay, and Uruguay). This technology is used on ~30 Mha every year in the region, although it is unknown how much of this area is under permanent no-till.

In the countries of Central and Eastern Europe, the Caucasus, and Central Asia, agricultural production is, at present, about 60–80 % of that in 1990, but is expected to grow by 15–40 % above 2001 levels by 2010, driven by the increasing wealth of these countries. A 10–14 % increase in arable land area is forecast for the whole of Russia due to agricultural expansion. The widespread application of intensive management technologies could result in a 2- to 2.5-fold rise in grain and fodder yields, with a consequent reduction of arable land, but may increase N fertilizer use. Decreases in fertilizer N use since 1990 have led to a significant reduction in N_2O emissions. But, under favorable economic conditions, the amount of N fertilizer applied will again increase, although unlikely to reach pre-1990 levels in the near future. US-EPA (2006b) projected a 32 % increase in N_2O emissions from soils in these two regions between 2005 and 2020, equivalent to an average rate of increase of 3.5 $MtCO_2$-eq/year.

OECD North America and OECD Pacific are the only developed regions showing a consistent increase in GHG emissions in the agricultural sector (18 % and 21 %, respectively, between 1990 and 2020) (Fig. 3.4). In both cases, the trend is largely driven by non-CO_2 emissions from manure management and N_2O emissions from soils. In Oceania, nitrogen fertilizer use has increased exponentially over the past 45 years with a 5- and 2.5-fold increase since 1990 in New Zealand and Australia, respectively. In North America, in contrast, nitrogen fertilizer use has remained stable; the main driver for increasing emissions is management of manure from cattle, poultry, and swine production and manure application to soils. In both regions, conservation policies have resulted in reduced CO_2 emissions from land conversion. Land clearing in Australia has declined by 60 % since 1990 with vegetation management policies restricting further clearing, while in North America, some marginal croplands have been returned to woodland or grassland.

Western Europe is the only region where, according to US-EPA (2006b), GHG emissions from agriculture are projected to decrease to 2020 (Fig. 3.4). This is associated with the adoption of a number of climate-specific and other environmental policies in the European Union, as well as economic constraints on agriculture.

All this has contributed to a rise in greenhouse gases in the atmosphere. Fossil fuels such as oil, coal, and natural gas supply most of the energy needed to run vehicles and generate electricity for industries, households, etc. The energy sector is responsible for about ¾ of the carbon dioxide emissions, 1/5 of the methane emissions, and a large quantity of nitrous oxide. It also produces nitrogen oxides (N_2O) and carbon monoxide (CO) which are not greenhouse gases but do have an influence on the chemical cycles in the atmosphere that produce or destroy greenhouse gases.

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Impacts of Climate Change on Agriculture

4

Abstract

Climate change and agriculture are interrelated processes, both of which take place on a global scale. Global warming is projected to have significant impacts on conditions affecting agriculture, including temperature, carbon dioxide, precipitation, sea-level rise, increasing ocean acidification, UV-B radiation, extreme weather events, glacier retreat and disappearance, ENSO effects on agriculture, and the interaction of these elements. These conditions determine the carrying capacity of the biosphere to produce enough food for the human population and domesticated animals. The overall effect of climate change on agriculture will depend on the balance of these effects. Assessment of the effects of global climate changes on agriculture might help to properly anticipate and adapt farming to maximize agricultural production.

The effects of carbon dioxide (CO_2) enrichment, without associated changes in climate, would probably be beneficial for agriculture. However, more severe warming, floods, and drought may reduce yields. Higher temperatures, however, could increase the rate of microbial decomposition of organic matter, adversely affecting soil fertility in the long run. An analysis of the biophysical impact of climate changes associated with global warming shows that higher temperatures generally hasten plant maturity in annual species, thus shortening the growth stages of crop plants. Also, studies analyzing the effects on pests and diseases suggest that temperature increases may extend the geographic range of some insect pests currently limited by temperature. The effects of increased ultraviolet-B (UV-B) radiation reduce yield in certain agricultural crops. Livestock may be at risk, both directly from heat stress and indirectly from reduced quality of their food supply. Fisheries will be affected by changes in water temperature that shift species ranges, make waters more hospitable to invasive species, and change life cycle timing.

Keywords

Temperature • Carbon dioxide enrichment • Precipitation • Sea-level rise • Increasing ocean acidification • UV-B radiation • Extreme weather events • Glacier retreat and disappearance • ENSO effects on agriculture

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Climate change has already significantly impacted agriculture (Lobell et al. 2011) and is expected to further impact food production directly and indirectly. Increase of mean temperature, changes in rain patterns, increased variability both in temperature and rain patterns, changes in water availability, the frequency and intensity of "extreme events," sea-level rise and salinization, and perturbations in ecosystems all will have profound impacts on agriculture, forestry, and fisheries (Gornall et al. 2010). The extent of these impacts will depend not only on the intensity and timing (periodicity) of the changes but also on their combination, which are more uncertain, and on local conditions. Anticipating appropriately the impacts of climate change on agriculture requires data, tools, and models at the spatial scale of actual production areas. Since the last IPCC report in 2007, some studies have attempted to anticipate these impacts and provide projections at such a scale, enabling us to have a more concrete vision of projected changes.

Climate change may lead to an increase in both crop and livestock productivity in mid- to high latitudes (IPCC 2007) and a decrease in tropical and subtropical areas. Among the most affected areas are economically vulnerable countries already food insecure and some important food-exporting countries. This will induce significant changes in trade, impacting prices and the situation of net food-importing countries. Consequently, climate change is expected to increase the gap between developed and developing countries as a result of more severe impacts in already vulnerable developing regions, exacerbated by their relatively lower technical and economical capacity to respond to new threats (Padgham 2009). Smallholders and pastoralists will suffer complex and localized impacts (IPCC 2007). According to the International Food Policy Research Institute (IFPRI), it will cause an increase of between 8.5 and 10.3 % in the number of malnourished children in all developing countries, relative to scenarios without climate change (Nelson et al. 2010).

Crop production is increasingly vulnerable to risks associated with new and evolving climatic changes. These are variations in environmental conditions that pose significant challenges to farmers, over and beyond those that are experienced "normally." The planet is facing more extreme weather events, such as heavy precipitation, higher coastal waters, geographic shifts in storm and drought patterns, and warmer temperatures (IPCC 2012).

Climate change is expected to cause substantial crop reductions in South Africa (up to 30 % by 2030 for maize production) and South Asia (up to 10 % for staples, such as rice, and more than 10 % for millet and maize) (Lobell et al. 2008). In mid- to high latitude, depending on the crop, productivity may increase slightly with increases in local mean temperatures of up to 1–3 °C. At lower latitudes, crop productivity will decrease even with a relatively minor change in temperature (IPCC 2007). Localized extreme events and sudden pest and disease outbreaks are already causing greater unpredictability in production from season to season and year to year and require rapid and adaptable management responses (FAO-PAR 2011). Climate change will have a significant impact on crop production (Table 4.1).

Table 4.1 Examples of projected climate change impacts on crop production (IPCC 2007; FAO 2008)

Event	Potential impact
Cold periods becoming warmer and shorter; over most land areas, days and nights becoming hotter (virtually certain)	Increased yields in colder environments; decreased yields in warmer environments; increased outbreaks of new insect pests and pathogens; potential impacts on crop production
Heavy precipitation events increasing in frequency over most areas (very likely)	Damage to crops; soil erosion; inability to cultivate land owing to water logging of soils
Drought-affected area increases (likely)	Land degradation and soil erosion; lower yields from crop damage and failure; loss of arable land
Intense tropical cyclone activity increases (likely)	Damage to crops
Extremely high sea levels increase in incidence (excludes tsunamis) (likely)	Salinization of irrigation water, estuaries, and fresh water systems; loss of arable land

It is likely that there will also be important effects on nutrition as a result of climate change. To date, studies mostly focus on cereals. There is a need to better capture all the nutritional consequences of the effects of climate change on livestock and on vegetables and wild foods, all of which have an important role in balanced diets and which are at risk (HLPE 2012; Bharucha and Pretty 2010).

In the last decade, an overwhelming consensus has emerged among scientists that the world has entered an era of rapid global climate change, much of which is attributable to greenhouse gas (GHG) emissions from human activity. Rapid global climate change is expected to impact agriculture by causing shifts in temperature, precipitation, soil quality, pest regimes, and seasonal growth patterns. To cope with climate change that is likely to be both rapid and unpredictable, agricultural systems must be resilient and able to adapt to change. Resilient agriculture systems are those that are more likely to maintain economic, ecological, and social benefits in the face of dramatic exogenous changes such as climate change and price swings. In the face of uncertainty, food production systems should be established which are diverse and relatively flexible, with integration and coordination of livestock and crop production.

The changes in agricultural production in all regions (globally) are consequence of changes in some physical key factors that are expected to be modified with climate change. This includes changes in sea level, CO_2, atmospheric O_3, extreme events, precipitation intensity, temperature, heat stress, etc. Soil erosion is a factor that is directly affected by climate conditions and has major consequences for agricultural productivity (Table 4.2).

Table 4.2 Climate change and related factors relevant to agricultural production at the global scale (Iglesias et al. 2009)

Climate and related physical factors	Expected direction of change	Potential impacts on agricultural production	Confidence level of the potential impact
Atmospheric CO_2	Increase from 360 ppm to 450–600 ppm (2005 levels now at 379 ppm)	Good for crops: increased photosynthesis; reduced water use. Increased biomass production and increased potential efficiency of physiological water use in crops and weeds. Modified hydrologic balance of soils due to C/N ratio modification. Changed weed ecology with potential for increased weed competition with crops	Medium
		Agroecosystems modification	High
		High N cycle modification	High
		Lower yield increase than expected	Low
Atmospheric O_3	Increase	Crop yield decrease	Low
Sea level	Rise by 10–15 cm. Increased in south and offset in north by natural subsistence/rebound	Loss of land, coastal erosion, flooding. Sea-level intrusion in coastal agricultural areas and salinization of groundwater supply	High
Extreme events	Poorly known, but significantly increased temporal and spatial variability expected. Increased frequency of floods and droughts	Crop failure	High
		Yield decrease	
		Competition for water	
Storminess	Increased wind speeds, especially in north. More intense rainfall events	Lodging, soil erosion, reduced infiltration of rainfall	Very low

(continued)

Table 4.2 (continued)

Climate and related physical factors	Expected direction of change	Potential impacts on agricultural production	Confidence level of the potential impact
Precipitation intensity	Intensified hydrological cycle, but with regional variations. Seasonal changes by ±10 %	Changed patterns of erosion and accretion. Changed storm impacts	High
		Changed occurrence of storm flooding and storm damage. Increased water logging. Increased pest damage	
Temperature	Increase by 1–2 °C. Winters warming more than summers. Increased frequency of heat waves	Faster, shorter, earlier growing seasons. Range moving north and to higher altitudes. Modifications in crop suitability and productivity. Heat stress risk. Increased evapotranspiration	High
		Changes in weeds, crop pests, and diseases. Changes in water requirements. Changes in crop quality	
	Differences in day–night temperature	Modifications in crop productivity and quality	Medium
Heat stress	Increases in heat waves	Damage to grain formation, increase in some pests	High
Variability	Increases across most climatic variables. Predictions uncertain	Changing risk of damaging events (heat waves, frost, droughts, floods) which affect crops and timing of farm operations	Very low

4.1 Projections

- The positive effect of increased CO_2 on crop growth plays a very critical role.
- A further increase of phytotoxic surface ozone (O_3) until the end of the century which may lead to considerable crop losses at least until 2030, especially in China (Van Deningen et al. 2009).
- The rise in sea levels and tropical cyclones are major threats to rice production in the Asian mega deltas especially in Vietnam, Bangladesh, and Myanmar.
- Agriculture contributes to approximately 30 % to the global GHG emissions (IPCC 2007; Bellarby et al. 2008) – a linear progression of industrial agriculture and its extension to all developing countries is a contradiction to climate protection.
- Looking at crop yields alone might be too narrow – the nutritional value of the future crops might counteract some of the yield gains.

It is frequently assumed that global change will bring higher temperatures, altered precipitation, and higher levels of atmospheric CO_2 (IPCC 1990). What might these changes mean for the biophysical response of agricultural crops?

The IPCC Third Assessment Report, published in 2001, concluded that the poorest countries would be hardest hit, with reductions in crop yields in most tropical and subtropical regions due to decreased water availability and new or changed insect pest incidence. In Africa and Latin America, many rainfed crops are near their maximum temperature tolerance, so that yields are likely to fall sharply for even small climate changes; falls in agricultural productivity of up to 30 % over the twenty-first century are projected. Marine life and the fishing industry will also be severely affected in some places.

Climate change induced by increasing greenhouse gases is likely to affect average crop yield to drop down to 50 % in Pakistan according to the UKMO scenario, whereas corn production in

Europe is expected to grow up to 25 % in optimum hydrological conditions.

More favorable effects on yield tend to depend to a large extent on realization of the potentially beneficial effects of carbon dioxide on crop growth and increase of efficiency in water use. Decrease in potential yields is likely to be caused by shortening of the growing period, decrease in water availability, and poor vernalization.

Global climatic changes can affect agriculture through their direct and indirect effects on the crops, soils, livestock, and pests (Table 4.3). Indirectly, there may be considerable effects on land use due to snow melt, availability of irrigation water, frequency and intensity of inter- and intra-seasonal droughts and floods, soil organic matter transformations, soil erosion, changes in pest profiles, decline in arable areas due to submergence of coastal lands, and availability of energy. Equally important determinants of food supply are socioeconomic environment, including government policies, capital availability, prices and returns, infrastructure, land reforms, and inter- and intranational trade that might be affected by the climatic change.

Table 4.3 Potential impacts of climate change on different sectors of agriculture (Aggarwal et al. 2009a)

Sector	Impact
Crop	Increase in ambient CO_2 concentration is beneficial since it leads to increased photosynthesis in several crops, especially those with C3 mechanism of photosynthesis such as wheat and rice, and decreased evaporative losses. Despite this, yields of major cereals crops, especially wheat, are likely to be reduced due to decrease in grain-filling duration, increased respiration, and/or reduction in rainfall/irrigation supplies
	Increase in extreme weather events such as floods, droughts, cyclones, and heat waves will adversely affect agricultural productivity
	Reduction in yields in the rainfed areas due to changes in rainfall pattern during monsoon season and increased crop-water demand
	Incidence of cold waves and frost events may decrease in future due to global warming, and it would lead to a decreased probability of yield loss associated with frost damage in northern India in crops such as mustard and vegetables
	Quality of fruits, vegetables, tea, coffee, aromatic, and medicinal plants may be affected
	Incidence of pest and diseases of crops to be altered because of more enhanced pathogen and vector development, rapid pathogen transmission, and increased host susceptibility
	Agricultural biodiversity is also threatened due to the decrease in rainfall and increase in temperature, sea-level rise, and increased frequency and severity of droughts, cyclones, and floods
Water	Demand for irrigation water would increase with rise in temperature and evapotranspiration rate. It may result in lowering of groundwater table at some places
	The melting of glaciers in the Himalayas will increase water availability in the Ganges, Brahmaputra, and their tributaries in the short run, but in the long run, the availability of water will decrease considerably
	A significant increase in runoff is projected in the wet season that, however, may not be very beneficial unless storage infrastructure is vastly expanded. This additional water in the wet season, on the other hand, may lead to increase in frequency and duration of floods
	The water balance in different parts of the world will be disturbed, and the quality of groundwater along the coastal track will be affected more due to intrusion of sea waters
Soil	Organic matter content, which is already quite low in soils, would become still lower. Quality of soil organic matter may be affected
	The residues of crops under the elevated CO_2 concentrations will have higher C:N ratio, and this may reduce their rate of decomposition and nutrient supply
	Rise in soil temperature will increase N mineralization, but its availability may decrease due to increased gaseous losses through processes such as volatilization and denitrification
	There may be a change in rainfall volume and frequency, and wind may alter the severity, frequency, and extent of soil erosion
	Rise in sea level may lead to saltwater ingression in the coastal lands, turning them less suitable for conventional agriculture

(continued)

Table 4.3 (continued)

Sector	Impact
Livestock	Climate change will affect fodder production and nutritional security of livestock. Increased temperature would enhance lignification of plant tissues, reducing the digestibility. Increased water scarcity would also decrease production of feed and fodder
	Major impacts on vector-borne diseases will be through expansion of vector populations in the cooler areas. Changes in rainfall pattern may also influence expansion of vectors during wetter years, leading to large outbreaks of diseases
	Global warming would increase water, shelter, and energy requirement of livestock for meeting the projected milk demands
	Climate change is likely to aggravate the heat stress in dairy animals, adversely affecting their reproductive performance
Fishery	Increasing temperature of sea and river water is likely to affect breeding, migration, and harvests of fishes
	Impacts of increased temperature and tropical cyclonic activity would affect the capture, production, and marketing costs of the marine fish
	Coral bleaching is likely to increase due to higher sea surface temperature

4.2 Carbon Dioxide (CO_2) Enrichment

Increasing atmospheric CO_2 concentration and simultaneous rises in temperature are influencing the global climate, henceforth affecting growth, development, and functioning of plants (Fig. 4.1). The primary effects of increased concentration of CO_2 include higher photosynthetic rate, increased light-use efficiency, reduction in transpiration and stomatal conductance, and improved water-use efficiency (Drake et al. 1997).

Scientists are in agreement that the levels of atmospheric CO_2 have increased in recent years. Prior to the industrial revolution, they were measured at 280 parts per million by volume (ppmv); currently the levels are around 380 ppmv. These levels have been steadily increasing by 1.9 ppm yearly since the year 2000, largely as a result of fossil fuel burning. Carbon dioxide is critical to photosynthesis (and thus plant growth). Scientists agree that even small increases in carbon dioxide result in more plant growth. It is likely that higher levels of CO_2 will result in higher harvestable crop yields. However, this depends critically on the availability of sufficient water and nutrients necessary for plant growth. Some scientists believe that one drawback to this increased productivity will be crops with lower nutrient and protein levels. If true, this could have a significant, widespread impact on long-term human health if additional fertilizers were not incorporated into crop production.

There are positive impacts of climate change in agriculture and forestry because plants can respond positively to higher concentrations of CO_2 in the atmosphere (LaSalle and Hepperly 2008). Higher levels of CO_2 increase the rate of photosynthesis and improve the efficiency of water use in plants, hence stimulating plant growth (known as CO_2 fertilization). Experiments where CO_2 concentrations have been increased by around 50 % (to approximately 550 ppm) have produced growth increases of around 15 % (Niggli et al. 2009) in crops and 10–50 % in tropical savanna grasses (US Geological Survey 2008). In studies where CO_2 has been increased up to 700 ppm, wheat yields have risen by 10–50 %, cotton biomass by 35 %, whole boll yields by 40 %, and lint yields by 60 % (Lal et al. 2003). Data supporting these conclusions have been collected in major field experimental studies in Australia (Wheat FACE experiment at Horsham in Victoria and OZFace experiment in Townsville, Queensland).

4.2.1 Impact on Photosynthesis

CO_2 is vital for photosynthesis, and the evidence is that increases in CO_2 concentration would

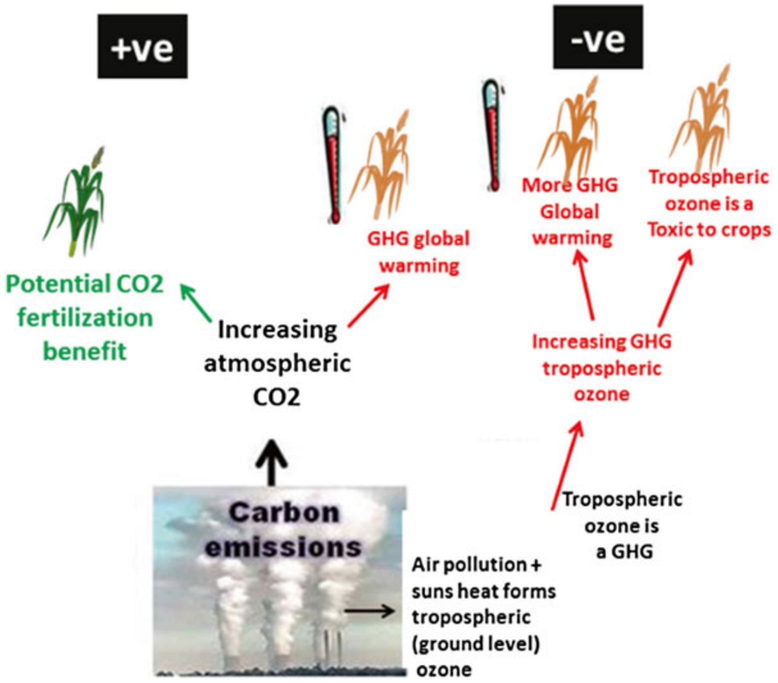

Fig. 4.1 Effect of increasing CO_2 concentration on crops

increase the rate of plant growth. Photosynthesis is the net accumulation of carbohydrates formed by the uptake of CO_2, so it increases with increasing CO_2 concentration. A doubling of CO_2 may increase the photosynthetic rate by 30–100 %, depending on other environmental conditions such as temperature and available moisture (Pearch and Bjorkman 1983). More CO_2 enters the leaves of plants due to the increased gradient of CO_2 between the external atmosphere and the air space inside the leaves. This leads to an increase in the CO_2 available to the plant for conversion into carbohydrate (Acock and Allen 1985). The difference between photosynthetic gain and loss of carbohydrate by respiration is the resultant growth.

There are, however, important differences between the photosynthetic mechanisms of different crop plants and hence in their response to increasing CO_2. Plant species with the C3 photosynthetic pathway (the first product in their biochemical sequence of reactions has three carbon atoms) use up some of the solar energy they absorb in a process known as photorespiration, in which a significant fraction of the CO_2 initially fixed into carbohydrates is reoxidized back to CO_2 (Hillel and Rosenzweig 1989). C3 species tend to respond positively to increased CO_2 because it tends to suppress rates of photorespiration (Fig. 4.1). This has major implications for food production in a high-CO_2 world because some of the current major food staples, such as wheat, rice, and soybean, are C3 plants. In total, 16 of the world's 20 most important food crops would benefit from increased carbon dioxide levels (Bianca 1976).

However, in C4 plants (those in which the first product has four carbon atoms), CO_2 is first trapped inside the leaf and then concentrated in the cells which perform the photosynthesis (Hillel and Rosenzweig 1989). Although more efficient photosynthetically under current levels of CO_2, these plants are less responsive to increased CO_2 levels than C3 plants (Fig. 4.2). The major C4 staples are maize, sorghum, sugarcane, and millet. Since these are largely tropical crops, and most widely grown in Africa, there is thus the suggestion that CO_2 enrichment will

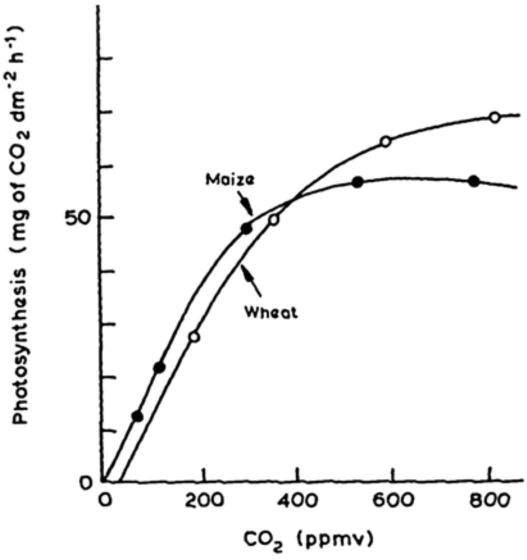

Fig. 4.2 Typical photosynthesis response of plants to CO_2. Net photosynthesis of wheat is about 70 mg of CO_2 dm h compared with maize (about 55 mg of CO_2 dm h) for equivalent light intensity (0.4 cal cm min). Maize is saturated at a lower CO_2 concentration (c. 450 ppmv) than wheat (c. 850 ppmv) (Adapted from Akita and Moss 1973)

benefit temperate and humid tropical agriculture more than that in the semiarid tropics and that if the effects of climatic changes on agriculture in some parts of the semiarid tropics are negative, then these may not be partially compensated by the beneficial effects of CO_2 enrichment as they might in other regions.

In addition it should be noted that although C4 crops account for only about one-fifth of the world's food production, maize alone accounts for 14 % of all production and about three-quarters of all traded grain. It is the major grain used to make up food deficits in famine-prone regions, and any reduction in its output could affect access to food in these areas.

C3 crops in temperate and subtropical regions could also benefit from reduced weed infestation. Fourteen of the world's 17 most troublesome terrestrial weed species are C4 plants in C3 crops (Morison 1989). The difference in response to increased CO_2 may make such weeds less competitive. In contrast, C3 weeds in C4 crops, particularly in tropical regions, could become more of a problem, although the final outcome will depend on the relative response of crops and weeds to climatic changes as well.

The different response of C3 and C4 crops may encourage changes in areas sown. It may, for example, accelerate the recent trend in India towards wheat, rice, and barley and away from maize and millets, a trend that has largely been driven by the promise of greater increases in yield. It may tend to reverse the current trend in temperate areas away from perennial rye grass (a C3 crop) towards silage maize (C4) as the major forage crop, and in the USA, it might encourage a tendency to switch from maize to soybean (C3) for forage.

Many of the pasture and forage grasses of the world are C4 plants, including important prairie grasses in North America and Central Asia and in the tropics and subtropics (Edwards and Walker 1983). The carrying capacity of the world's major rangelands is thus unlikely to benefit substantially from CO_2 enrichment. Much, of course, will depend on the parallel effects of climatic changes on the yield potential of these different crops.

The actual amount of increase in usable yield rather than of total plant matter that might occur as a result of increased photosynthetic rate is also problematic. In controlled environmental studies, where temperature and moisture are optimal, the yield increase can be substantial, averaging 36 % for C3 cereals such as wheat, rice, barley, and sunflower under a doubling of ambient CO_2 concentration (Table 4.4).

Little is also known about possible changes in yield quality under increased CO_2. The nitrogen content of plants is likely to decrease, while the carbon content increases, implying reduced protein levels and reduced nutritional levels for livestock and humans. This, however, may also reduce the nutritional value of plants for pests, so that they need to consume more to obtain their required protein intake.

4.2.2 Impact on Water Use by Plants

Just as important may be the effect that increased CO_2 has on the closure of stomata, small openings

Table 4.4 Mean predicted growth and yield increases for various groupings of C3 species for a doubling of atmospheric CO_2 concentration from 330 ppmv to 660 ppmv (Warrick et al. 1986)

	Immature crops		Mature crops	
Crops	No. of records	% increase of biomass	No. of records	% increase of marketable yield
Fiber crops – cotton (*Gossypium hirsutum*)	5	124	2	104
Vegetable crops – cucumber, eggplant, okra, pepper, tomato	15	40	12	21
Grain crops – barley, rice, sunflower, wheat	6	20	15	36
Leaf crops – cabbage, white clover, fescue, lettuce, Swiss chard	5	37	9	19
Pulses – bean, pea, soybean	18	43	13	17
Root crops – sugar beet, radish	10	49	–	–
C3 weeds[a]	10	43	–	–
Trees – cotton (*Gossypium deltoides*)	14	26	–	–
Av. of all C3	(83)	40 ± 7	(51)	26 ± 9

[a] *Crotalaria spectabilis*, *Desmodium paniculatum*, jimson weed (*Datura stramonium*), pig weed (*Amaranthus retroflexus*), rag weed (*Ambrosia artemissiifolia*), sickle pod (*Cassia obtusifolia*), and velvet leaf (*Abutilon theophrasti*)

in leaf surfaces through which CO_2 is absorbed and through which water vapor is released by transpiration. The stomatal conductances of 18 agricultural species have been observed to decrease markedly (by 36 %, on average) in an atmosphere enriched by doubled CO_2 (Morison and Gifford 1984). This tends to reduce the water requirements of plants by reducing transpiration (per unit leaf area), thus improving what is termed water-use efficiency (the ratio of crop-biomass accumulation to the water used in evapotranspiration). A doubling of ambient CO_2 concentration causes about a 40 % decrease in stomatal aperture in both C3 and C4 plants (Morison 1987) which may reduce transpiration by 23–46 % (Cure and Acock 1986). This might well help plants in environments where moisture currently limits growth, such as in semiarid regions. Increases in photosynthesis and resistance with higher CO_2 have been shown to occur at less than optimal levels of other environmental variables, such as light, water, and some of the mineral nutrients (Acock and Allen 1985).

In summary, we can expect a doubling of atmospheric CO_2 concentrations from 330 to 660 ppmv to cause a 10–50 % increase in growth and yield of C3 crops (such as wheat, soybean, and rice) and a 0–10 % increase for C4 crops (such as maize and sugarcane) (Warrick et al. 1986). Much depends, however, on the prevailing growing conditions. Our present knowledge is based on a few experiments mainly in glass houses and has not yet included extensive study of response in the field under subtropical conditions. Thus, although there are indications that, overall, the effects of increased CO_2 could be distinctly beneficial and could partly compensate for some of the negative effects of CO_2-induced changes of climate, we cannot at present be sure that this will be so.

4.2.3 Physiological Effects of CO_2

The study of agricultural impacts of trace gas-induced climate change is complicated by the fact that increasing atmospheric CO_2 has other effects on crop plants besides its alteration of their climate regime. These are often called “fertilizing” effects, because of their perceived beneficial physiological nature. Specifically, most plants growing in enhanced CO_2 exhibit increased rates of net photosynthesis. The higher photosynthesis rates are then manifested in higher leaf area, dry matter production, and yield for many crops (Acock and Allen 1985). In several cases, high CO_2 has contributed to upward shifts in temperature optima for photosynthesis (Jurik et al. 1984) and to enhanced growth with higher temperatures (Idso et al. 1987); other studies, however, have not shown such benefits (Baker et al. 1989).

Temperate crops may benefit more from increasing CO_2 than tropical crops. In crop species with the C3 pathway characteristic of nontropical plants (e.g., wheat, soybean, cotton), CO_2 enrichment has been shown to decrease photorespiration, the rapid oxidation of recently formed sugars in the light, a process which lowers the efficiency of overall photosynthesis. C4 crops which are particularly characteristic of tropical and warm arid regions (e.g., maize, sorghum, and millet) are more efficient photosynthetically under current CO_2 levels than C3 plants (because they fix CO_2 into malate in their mesophyll cells before delivering it to the RuBP enzyme in the bundle-sheath cells). Because of this CO_2-concentrating and photorespiration-avoiding mechanism, experimental data show that C4 plants are less responsive to CO_2 enrichment (Acock and Allen 1985).

The physiological effects of high levels of atmospheric CO_2 described above have been observed under controlled experimental conditions. In the open field, however, their magnitude and significance are still largely untested, and their importance relative to the predicted large-scale climatic effects uncertain. Greenhouse and field-chamber environments tend to be much smaller, less variable, and more protected from wind than field conditions. Furthermore, physiological feedback mechanisms such as starch accumulation or lack of sink (i.e., growing, storing, or metabolizing tissue) for the products of photosynthesis may limit the extent to which the "fertilizing" CO_2 effects may be realized. Finally, if trace gas emissions continue to grow unchecked, their climate warming effect is projected to continue even up to 2,000 ppm (Manabe and Bryan 1985), but the beneficial boost to photosynthesis appears to level off at about 400 ppm for C4 crops and about 800 ppm for C3 crops (Akita and Moss 1973).

4.2.4 CO_2 Fertilization

Increasing atmospheric CO_2 concentrations can also directly affect plant physiological processes of photosynthesis and transpiration (Field et al. 1995). Therefore, any assessment of the impacts of CO_2-induced climate change on crop productivity should account for the modification of the climate impact by the CO_2 physiological impact. The CO_2 physiological response varies between species, and, in particular, two different pathways of photosynthesis (named C3 and C4) have evolved and these affect the overall response. The difference lies in whether ribulose-1, 5-bisphosphate carboxylase–oxygenase (RuBisCO) within the plant cells is saturated by CO_2 or not. In C3 plants, RuBisCO is not CO_2-saturated in present-day atmospheric conditions, so rising CO_2 concentrations increase net uptake of carbon and thus growth. The RuBisCO enzyme is highly conserved in plants, and as such it is thought that the response of all C3 crops including wheat and soybeans will be comparable. Theoretical estimates suggest that increasing atmospheric CO_2 concentrations to 550 ppm could increase photosynthesis in such C3 crops by nearly 40 % (Long et al. 2004). The physiology of C4 crops, such as maize, millet, sorghum, and sugarcane, is different. In these plants, CO_2 is concentrated to three to six time's atmospheric concentrations, and thus, RuBisCO is already saturated. Thus, rising CO_2 concentrations confer no additional physiological benefits. These crops may, however, become more water-use efficient at elevated CO_2 concentrations as stomata do not need to stay open as long for the plant to receive the required CO_2. Thus, yields may increase marginally as a result (Long et al. 2004).

Experiments under idealized conditions show that a doubling of atmospheric CO_2 concentration increases photosynthesis by 30–50 % in C3 plant species and 10–25 % in C4 species (Ainsworth and Long 2005). Crop yield increase is lower than the photosynthetic response; increases of atmospheric CO_2 to 550 ppm would on average increase C3 crop yields by 10–20 % and C_4 crop yields by 0–10 % (Long et al. 2004; Ainsworth and Long 2005).

Despite the potential positive effects on yield quantities, elevated CO_2 may, however, be detrimental to yield quality of certain crops. For example, elevated CO_2 is detrimental to wheat flour quality through reductions in protein content (Sinclair et al. 2000).

Without CO_2 fertilization, many regions, especially in the low latitudes, suffer a decrease in productivity by 2050. In contrast, by including CO_2 fertilization, all but the very driest regions show increases in productivity. If CO_2 fertilization is strong, North America and Europe may benefit from climate change at least in the short term. However, regions such as Africa and India are nevertheless still projected to experience up to 5 % losses by 2050, even with strong CO_2 fertilization. These losses increase up to 30 % if the effects of CO_2 fertilization are omitted. In fact without CO_2 fertilization, all regions are projected to experience a loss in productivity owing to climate change by 2050.

A reduction in CO_2 emissions would be expected to reduce the positive effect of CO_2 fertilization on crop yields more rapidly than it would mitigate the negative impacts of climate change. Even if GHG concentrations rose no further, there is a commitment to a certain amount of further global warming (IPCC 2007). Stabilization of CO_2 concentrations would therefore halt any increase in the impacts of CO_2 fertilization, while the impacts of climate change could still continue to grow. Therefore, in the short term, the impacts on global food production could be negative. However, estimates suggest that stabilizing CO_2 concentrations at 550 ppm would significantly reduce production losses by the end of the century (Tubiello and Fischer 2006).

For all species, higher water-use efficiencies and greater root densities under elevated CO_2 in field systems may alleviate drought pressures (Centritto 2005). This could offset some of the expected warming-induced increase in evaporative demand, thus easing the pressure for more irrigation water. This may also alter the relationship between meteorological drought and agricultural/hydrological drought; an increase in meteorological drought may result in a smaller increase in agricultural or hydrological drought owing to increased water-use efficiency of plants (Betts et al. 2007).

Table 4.5 Effect of elevated CO_2 level on yield of selected crops (Singh et al. 2010)

Parameters	Ambient CO_2 level (380 ppm)	Elevated CO_2 level (550 ppm)	CO_2 fertilization effect (%)
Green gram			
Biological yield (g m^{-2})	270	295	9
Seed yield (g m^{-2})	92	102	11
Soybean			
Biological yield (g m^{-2})	463	530	14
Seed yield (g m^{-2})	190	220	16
Chickpea			
Biological yield (g m^{-2})	694	800	15
Seed yield (g m^{-2})	213	258	21
Wheat			
Biological yield (g m^{-2})	1,068	1,260	18
Seed yield (g m^{-2})	442	516	17

4.2.5 Effect on Yield

During 2007–2009, an experiment was conducted at the Indian Agricultural Research Institute farm, New Delhi, India, on four crops (green gram, soybean, chickpea, and wheat) inside the FACE ring (Singh et al. 2010). It was found that biomass as well as grain yield increased in all these crops under the elevated CO_2 condition (550 ppm) (Table 4.5). The enhancement in yield was associated with increase in the number of pods/plant, number of seeds/pod, number of spikes/m^2, number of grains/spike, etc.

4.3 Elevated Temperatures

The global temperature has increased by 0.74 °C during the past 100 years. The recent report of IPCC (2007) has reconfirmed the increasingly strong evidence of global climate change and has projected that the average atmospheric temperature across the world would rise by 1.8–4.0 °C

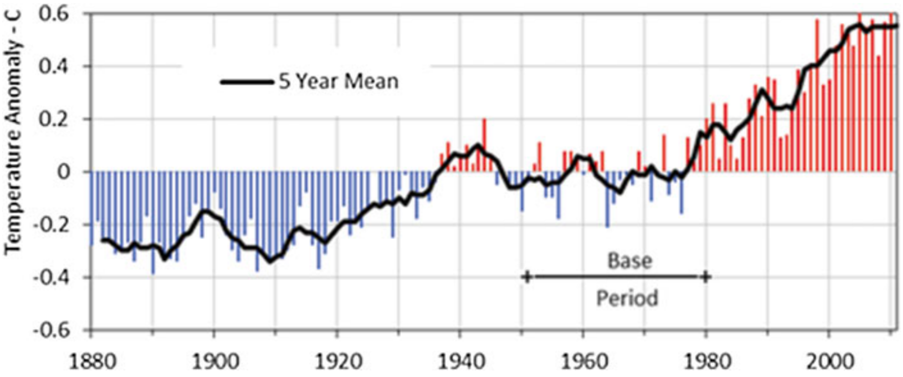

Fig. 4.3 Global temperature, 1800–2006 (globalissues.org)

by the end of the twenty-first century, depending upon the adoption of developmental pathways by countries. Increasing temperatures and carbon dioxide levels in the atmosphere along with the uncertainties in annual precipitations will have adverse effects on agriculture. Biomass and yield tend to decline with increasing temperature, as higher temperatures shorten crop duration, enhance respiration, and reduce time for radiation interception (Rawson et al. 1995). As yields in some of the most productive regions of the world are approaching a plateau or even declining (Pathak et al. 2003), the likely effect of climate change on crop production adds to the already complex problem. It is a major challenge to evaluate the impact of rising temperature on crop yield.

In the 1880–1935 period, the temperature anomaly was consistently negative. In contrast, since 1980 the anomaly has been consistently positive. The 1917 temperature anomaly (–0.47 °C) was the lowest year on record. Since 1917, global temperature has warmed, with the most recent years showing the highest anomalies of +0.6 °C in the past 120 years (Fig. 4.3 and Table 4.6).

When the optimal range of temperature values for a crop in a particular region is exceeded, crops tend to respond negatively, resulting in a drop in yield. The optimal temperature varies for different crops. Temperatures greater than 36 °C cause corn pollen to lose viability, while temperatures higher than 20 °C depress tuber initiation and bulking in potato.

Table 4.6 Global top 10 warmest years (Jan–Dec)

Global top 10 warmest years (Jan–Dec)	Anomaly °C	Anomaly °F
2010	0.62	1.12
2005	0.62	1.12
1998	0.60	1.08
2003	0.58	1.04
2002	0.58	1.04
2009	0.56	1.01
2006	0.56	1.01
2007	0.55	0.99
2004	0.54	0.97
2001	0.52	0.94

Source: Annual State of the Climate Global Analysis, National Climatic Data Center, NOAA, December 2010

Most agronomic crops are sensitive to episodes of high temperature. Air temperatures between 45 and 55 °C that occur for at least 30 min directly damage crop leaves in most environments; even lower temperatures (35–40 °C) can be damaging if they persist longer. Vulnerability of crops to damage by high temperatures varies with developmental stage. Prolonged hot spells can be especially damaging (Mearns et al. 1984). Critical stages for high temperature injury include seedling emergence in most crops, silking and tasseling in corn (Shaw 1983), grain filling in wheat (Johnson and Kanemasu 1983), and flowering in soybeans (Mederski 1983). Soybean is one crop that seems to have the ability to recover from heat stress, perhaps because it is indeterminate (i.e., grows continuously).

Many scientists project that the average temperatures throughout the world will rise in the next few decades. Much of this warming could occur at night, but the models are not clear on this. If temperatures increase, cooler areas of the world might be more habitable for some of the main food crops grown, thus expanding the areas in which certain crops could be grown or moving their ranges north. For example, less frequent freezes could allow citrus to move north from its current range in Florida to other areas of the Southeast. In areas where crops are being grown in their warmest productive temperature ranges already, heat stress or increased disease could reduce yields. However, research on new crop varieties and technological advances could improve yields in spite of reductions due to temperature increases. A report from the IPCC is optimistic that general crop yields for the next century could increase in a range from 5 to 20 % during the first few decades of the twenty-first century, and they expect the crop yield to remain somewhat steady (but positive) through the rest of the century. If climate change reduces the global amount of arable land, however, total yields could still decrease.

4.3.1 Interactions with Thermal Regimes

Higher temperatures in general hasten plant maturity in annual species, thus shortening the growth stages during which pods, seeds, grains, or bolls can absorb photosynthetic products. This is one reason yield is lower in the tropics. Because crop yield depends on both the rate of carbohydrate accumulation and the duration of the filling periods, the economic yields of both temperate and tropical crops grown in a warmer and CO_2-enriched environment may not rise substantially above present levels, despite increases in net photosynthesis (Rose 1989).

Because temperate and tropical regions differ in both current temperature and the temperature rise predicted for climate change, the relative magnitudes of combined CO_2 and temperature effects will likely be different in the different regions. In the mid-latitudes, higher temperatures may shift biological process rates towards optima, and beneficial effects are likely to ensue. Increases in temperature will also lengthen the frost-free season in temperate regions, allowing for longer duration crop varieties to be grown and offering the possibility of growing successive crops (moisture conditions permitting). In tropical locations where increased temperatures may move beyond optima, negative consequences may dominate.

Both the mean and extreme temperatures that crops experience during the growing season will change in both temperate and tropical areas. Extreme temperatures are important because many crops have critical thresholds both above and below which crops are damaged. In general, higher temperatures should decrease cold damage and increase heat damage. Agroclimatic zones are expected to shift poleward as lengthening and warming growing seasons allow new or enhanced crop production (soil resources permitting) (Rosenzweig 1985).

4.3.2 Crops and Temperature

Many untested assumptions lie behind efforts to project global warming's potential influence on crops. In addition to the magnitude and pace of change, the stage of growth during which a crop is exposed to drought or heat is important. When a crop is flowering or fruiting, it is extremely sensitive to changes in temperature and moisture; during other stages of the growth cycle, plants are more tolerant.

Moreover, temperature and seasonal rainfall patterns vary from year to year and region to region, regardless of long-term trends in climate. Temperature and rainfall changes induced by climate change likely will interact with atmospheric gases, fertilizers, insects, plant pathogens, weeds, and the soil's organic matter to produce unanticipated responses.

Despite these uncertainties, an average global temperature rise of slightly more than one-half degree centigrade would lengthen the frost-free growing season in the Corn Belt by 2 weeks (Morison 1987). However, if temperatures continue to increase beyond a specific threshold, a crop's productive summer growing season could become shorter, thus reducing the yield (Cure and Acock 1986).

Crops such as rice, potatoes, corn, wheat, and soybeans have optimal microclimate temperatures and an optimal growing season. Recognizing these optimal levels will enable farmers to alter their mix of crops in response to their region's changing temperatures. However, turning to different crops will not guarantee that a farmer will produce the same amount of food or enjoy the same profits.

4.3.3 Effects on Growth Rates

In high mid-latitude regions (above 45°), at high latitudes (above 60°), and at high altitudes, temperature is frequently the dominant climatic control on crop and animal growth. It determines the potential length of the growing and grazing seasons and generally has a strong effect on the timing of developmental processes and on rates of expansion of plant leaves. The latter, in turn, affects the time at which a crop canopy can begin to intercept solar radiation and thus the efficiency with which solar radiation is used to make plant biomass (Monteith 1981).

In general, plant response to temperature follows as indicated in Fig. 4.4. Development does not begin until temperature exceeds a threshold; then the rate of development increases broadly linearly with temperature to an optimum, above which it decreases broadly linearly (Squire and Unsworth 1988).

However, the effect of this development on plant biomass depends on whether the growth habit of the plant is determinate (i.e., it has a discrete life cycle which ends when the grain is mature, such as in cereals) or whether it is indeterminate (i.e., it continues to grow and yield throughout the season, such as in grasses and root crops). Temperature increase shortens the reproductive phase of determinate crops, decreasing the time during which the canopy exists and thus the period during which it intercepts light and produces biomass (Fig. 4.4b). The canopy of indeterminate crops, however, continues to intercept light until it is reduced by other events such as frost or pests, and the duration of the canopy increases when increased temperatures extend the season over which crops can grow (e.g., by delaying the first frosts of autumn) (Fig. 4.4c). An increase in temperature above the base but not exceeding optimum temperatures should therefore generally lead to lower yields in cereals and higher yields of root crops and grassland, though higher temperatures may also lead to higher rates of evaporation and therefore reduced moisture availability that can also be expected to affect yields.

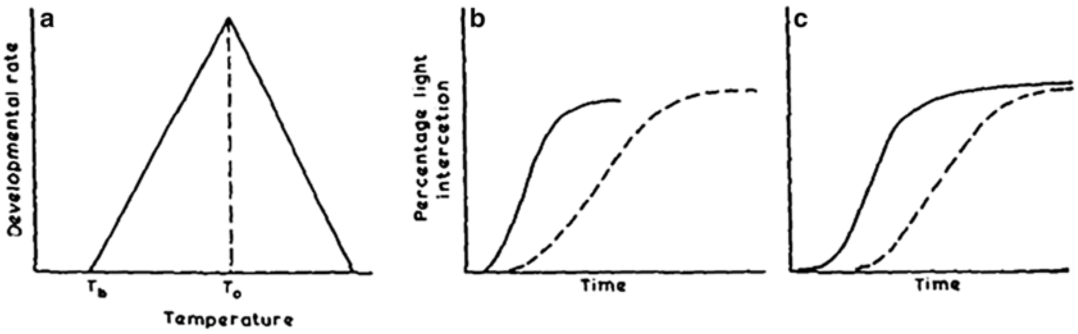

Fig. 4.4 Temperature and development of canopy expansion. (**a**) Idealized relation between developmental rate and temperature. Development does not begin until temperature exceeds a threshold (T_b, the base temperature); then developmental rate increases linearly with temperature to an optimum (T_o), above which it decreases linearly. (**b**) and (**c**) Effect of temperature on the relation between time and fractional interception of solar radiation by a canopy, for a determinate (**b**), and indeterminate (**c**) species (----- cooler; —— warmer) (Squire and Unsworth 1988)

4.3.4 Effects on Growing Seasons

One of the most important effects of an increase in temperature, particularly in regions where agricultural production is currently limited by temperature, would be to extend the growing season available for plants (e.g., between last frost in spring and first frost in autumn) and reduce the growing period required by crops for maturation.

The effects of warming on length of growing season and growing period will vary from region to region and from crop to crop. For wheat in Europe, for example, the growing season is estimated to lengthen by about 10 days per °C and in central Japan by about 8 days per °C (Yoshino et al. 1988). In general the conclusion is that increased mean annual temperatures, if limited to two or three degrees, could generally be expected to extend growing seasons in high mid-latitude and high-latitude regions. Increases of more than this could increase evapotranspiration rates to a point where reduced crop-water availability begins to limit the growing season.

4.3.5 Reduction in Crop Yield

Higher growing season temperatures can significantly impact agricultural productivity, farm incomes, and food security. In mid- and high latitudes, the suitability and productivity of crops are projected to increase and extend northwards, especially for cereals and cool season seed crops. Crops prevalent in Southern Europe such as maize, sunflower, and soybeans could also become viable further north and at higher altitudes. Here, yields could increase by as much as 30 % by the 2050s, dependent on crop (Ewert et al. 2005). For the coming century, large gains have been simulated in potential agricultural land for the regions such as the Russian Federation, owing to longer planting windows and generally more favorable growing conditions under warming, amounting to a 64 % increase over 245 million hectares by the 2080s. However, technological development could outweigh these effects, resulting in combined wheat yield increases of 37–101 % by the 2050s (Ewert et al. 2005).

Rise in the mean temperature above a threshold level will cause a reduction in agricultural yields. A change in the minimum temperature is more crucial than a change in the maximum temperature. Grain yield of rice, for example, declined by 10 % for each 1 °C increase in the growing season minimum temperature above 32 °C (Pathak et al. 2003). The climate change impact on the productivity of rice in Punjab (India) has shown that with all other climatic variables remaining constant, temperature increases of 1 °C, 2 °C, and 3 °C would reduce the grain yield of rice by 5.4 %, 7.4 %, and 25.1 %, respectively (Aggarwal et al. 2009b).

Even moderate levels of climate change may not necessarily confer benefits to agriculture without adaptation by producers, as an increase in the mean seasonal temperature can bring forward the harvest time of current varieties of many crops and hence reduce final yield without adaptation to a longer growing season.

In areas where temperatures are already close to the physiological maxima for crops, such as seasonally arid and tropical regions, higher temperatures may be more immediately detrimental, increasing the heat stress on crops and water loss by evaporation. A 2 °C local warming in the mid-latitudes could increase wheat production by nearly 10 %, whereas at low latitudes, the same amount of warming may decrease yields by nearly the same amount (Fig. 4.5). Different crops show different sensitivities to warming. It is important to note that the large uncertainties in crop yield changes for a given level of warming (Fig. 4.5). By fitting statistical relationships between growing season temperature, precipitation, and global average yield for six major crops, Lobell and Field (2007) estimated that warming since 1981 has resulted in annual combined losses of 40 million tons or US$5 billion (negative relationships between wheat, maize, and barley with temperature).

Whether crops respond to higher temperatures with an increase or decrease in yield depends on whether they are determinate or indeterminate and whether their yield is currently strongly limited by insufficient warmth. In cold regions very near the present-day limit to arable agriculture,

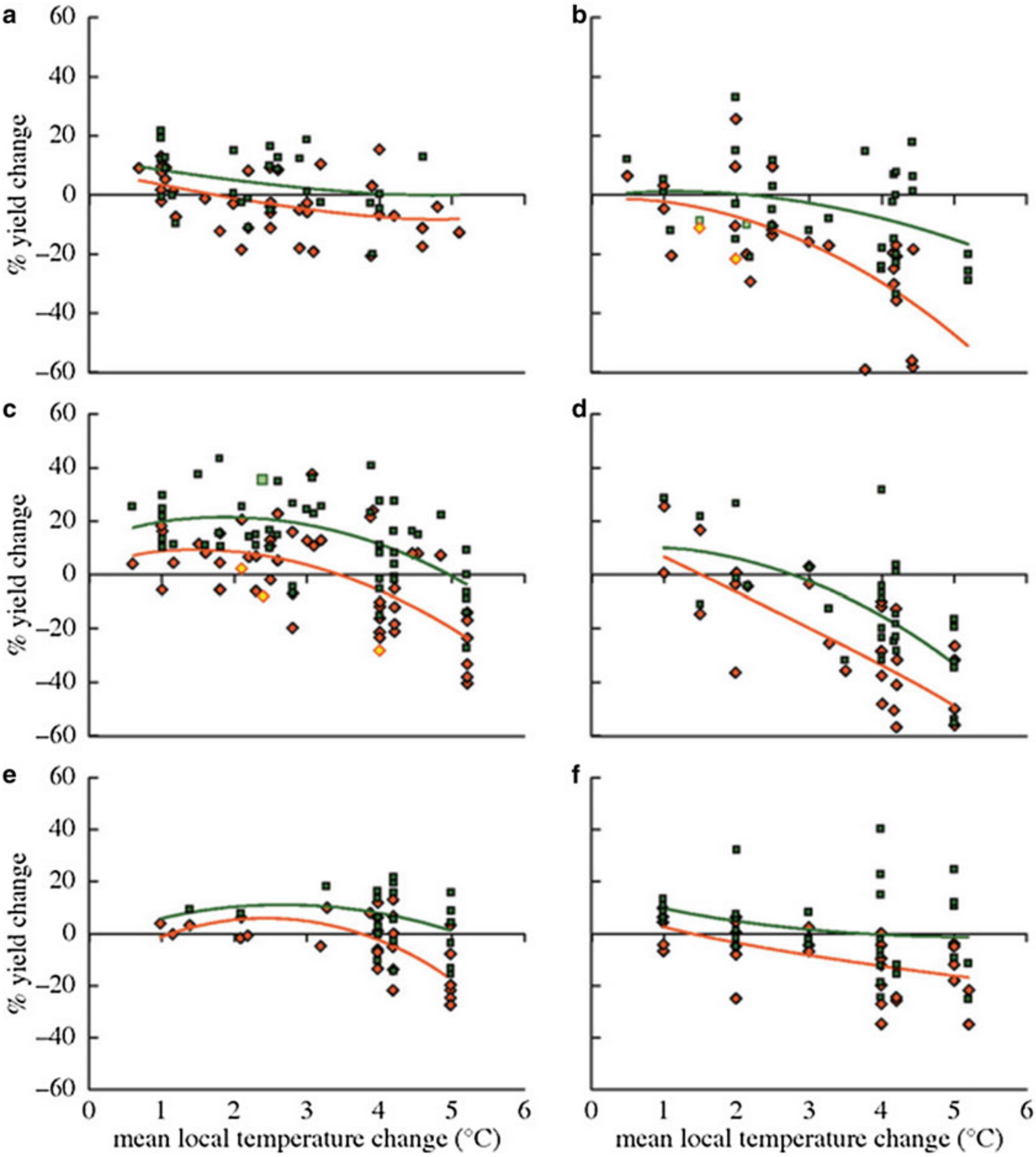

Fig. 4.5 Sensitivity of cereal (**a**, **b**) maize (mid- to high latitude and low latitude), (**c**, **d**) wheat (mid- to high latitude and low latitude), and (**e**, **f**) rice (mid- to high latitude) to climate change as determined from the results of 69 studies, against temperature change. Results with (*green*) and without (*red*) adaptation are shown (Easterling et al. 2007)

any temperature increase, even as much as the 7–9 °C indicated for high latitudes under a doubling of CO_2, can be expected to enhance yields of cereal crops. For example, near the current northern limit of spring wheat production in the European region of the USSR yields increase about 3 % per °C, assuming no concurrent change in rainfall. In Finland, the marketable yield of barley increases 3–5 % per °C, and in Iceland hay yields increase about 15 % per °C (Kettunen et al. 1988).

Away from current temperature-constrained regions of farming and in the core areas of present-day cereal production such as in the Corn

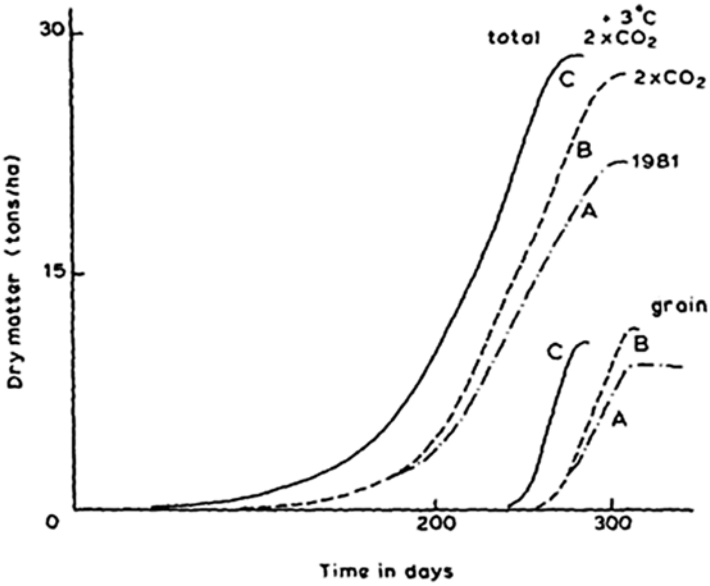

Fig. 4.6 Modeled responses of total dry matter production and grain yield of winter wheat. *A*, curves modeled from the 1981 climatic conditions at Brooms Barn, Bury St. Edmunds (UK); *B*, simulates the effect of a doubling of CO_2 concentration, and *C*, the effect of both a doubled CO_2 concentration and a rise in mean temperature of 3 °C (Squire and Unsworth 1988)

Belt of North America, the European lowlands, and the Soviet Ukraine, increases in temperature would probably lead to decreased cereal yield due to a shortened period of crop development (Smith and Tirpak 1990). In eastern England, for example, a 3 °C rise in mean annual temperature is estimated to reduce winter-wheat yield by about 10 %, although the direct effect of a doubling of ambient atmospheric CO_2 might more than compensate for this (Fig. 4.6).

In other mid-latitude regions, much would depend on possible changes in rainfall. For example, in the Volgograd region, just east of the Ukraine, spring wheat yields are estimated to fall only a small amount with a 1 °C increase in mean temperature during the growing season, though they could increase or decrease substantially if the temperature change was accompanied by an increase or decrease of rainfall (Table 4.7).

Every 1 °C increase in temperature reduces wheat production by 4–5 million tons. Loss shall be only 1–2 million tons if farmers could plant in time (Fig. 4.7).

Yields of root crops such as sugar beet and potatoes, with an indeterminate growth habit, can be expected to see an increase in yield with increasing temperatures, provided these do not exceed temperatures optimal for crop development (Squire and Unsworth 1988).

Table 4.7 Response of spring wheat yield (as % of the long-term mean) to variations in air temperature and precipitation during the growing season (Pallasovka, Volgograd region) (Nikonov et al. 1988)

	Air temperature (°C)				
Precipitation (mm)	−1.0	−0.5	0	+0.5	+1.0
−40	79	79	76	76	76
−20	92	92	89	89	89
0	104	103	100	100	99
+20	115	114	110	109	108
+40	125	124	120	118	117

A temperature gradient tunnel (TGT) installed at Indian Agricultural Research Institute Farm, New Delhi, India, was used to assess the impact of high temperature on crop growth and yield during rabi season of 2008–2009. It was found that TGTs were able to maintain the temperature gradient in wheat and chickpea crops. The study revealed that high temperature reduced the duration of crop growth in both wheat and chickpea. The period for 50 % flowering in wheat and chickpea crops was decreased by 5 days with 2.9 °C and by 6 days with 3.1 °C rise in temperature. Rise in temperature inside the TGTs also led to reduction in biomass and grain yield of both wheat and chickpea crop (Table 4.8).

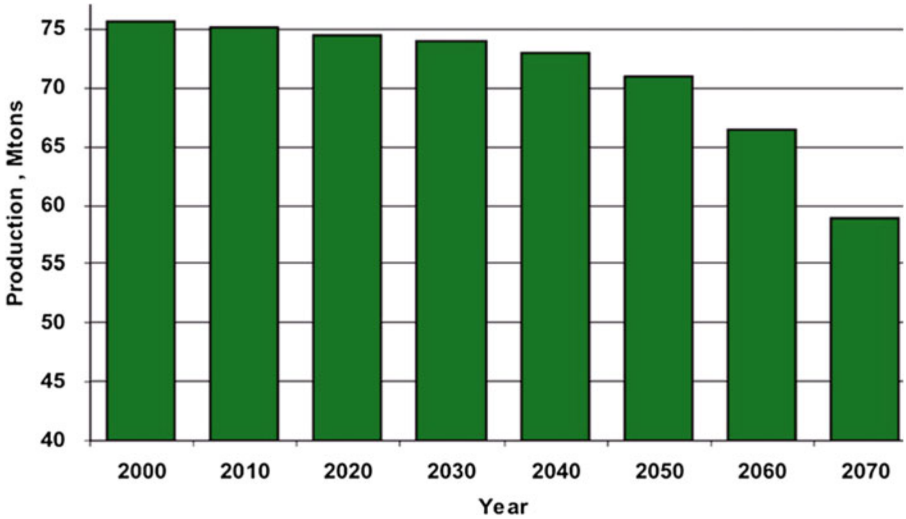

Fig. 4.7 Potential impact of climate change on wheat production in India

Table 4.8 Effect of high temperature on yield of wheat and chickpea crops

Temp. gradient (°C)	Biological yield (g m^{-2})	Grain/seed yield (g m^{-2})
Wheat		
0	1,216	368
+1.0	1,060	320
+2.1	1,000	295
+2.5	914	280
+2.9	798	251
Chickpea		
0	773	228
+0.9	722	197
+2.3	695	195
+2.6	638	192
+3.1	606	190

4.3.6 Effects on Moisture Availability

Changes of temperature would also have an effect on moisture availability for crop growth, whether or not levels of rainfall remained unchanged. In general, at mid-latitudes, evaporation increases by about 5 % for each 1 °C of mean annual temperature. Thus, if mean temperature were to increase in the east of England by 2 °C, potential evaporation would increase by about 9 % (assuming no change in rainfall). The effect of this would be small in the early part of the growing season, but after mid-July the soil moisture deficit would be considerably larger than at present, and, for some crops, this implies substantially increased demand for irrigation (Rowntree et al. 1989). Of course, the amount of water available for plant growth is affected by a combination of climatic and non-climatic variables such as precipitation, temperature, sunshine, wind speed as well as soil porosity, slope, etc.

The effects of high temperature and soil moisture on major field crops in the USA are presented in Table 4.9.

The increased temperature would result in more water shortages, and the demand for irrigation water would rise. Increase in air temperature will lead to more potential evapotranspiration in the areas south of 40°N. Likewise, water shortage due to climate change would result in about 20 % net decline in the rice yields in India.

4.3.7 Effects on Livestock

A rise in temperature could also have a significant effect on the performance of farm animals, in addition to the effects that might flow from altered yields of grassland and forage crops. Young animals tend to be less tolerant of a wide range of temperature

Table 4.9 High temperature and soil moisture effects on major field crops in the US

Crop	Effects
Corn	Temperature higher than 36 °C causes pollen to lose viability
	Extremely sensitive to soil moisture deficits. Four days of visible wilting in (a) the period before tasseling reduces yield by 10–25 %, (b) between the week before tasseling and the milk stage reduces yield by more than 50 %, in (c) the soft dough stage, decreases yield by 40 %
	Aflatoxin concentration rises when the crop has a water deficit
	Very intolerant to flooding except after the silking stage; the effect of flooding depends on temperature. Before the 6th leaf stage the crop does not survive more than 4 days of flooding if the temperature is less than 25 °C and less than 24 h if the temperature is more than 25 °C. When the crop is less than 15 cm high, 24 h of flooding reduces yield by 18 % at any temperature
	Continuous soil saturation causes long-term problems related to rot development and increased damage by diseases (e.g., crazy top and common smut)
Soybean	Soil temperature higher than 35 °C at planting causes seedling death. Very sensitive to temperatures above 35 °C during the first 3 weeks after bloom. Great ability to recover from temperature stress at other times
	Sensitive to soil moisture deficits and drought at planting and from bloom to pod-fill. Very sensitive to soil moisture deficits during pod-filling and seed enlargement
	Relatively tolerant to excess soil humidity, but saturated soils increase the risk of seedling diseases especially at temperatures above 32 °C
Wheat	Temperature above 30 °C for more than 8 h can reverse vernalization
	Flowering, pollination, and grain filling sensitive to water stress
	Excess soil moisture causes water logging and increases risk of fungal infestations
Cotton	Temperature above 40 °C for more than 6 h causes bolls to abort
	Relatively tolerant to temperatures under 40 °C
	Sensitive to soil moisture deficits and drought at planting and flowering
	Excess rainfall at maturity damages quality of crop

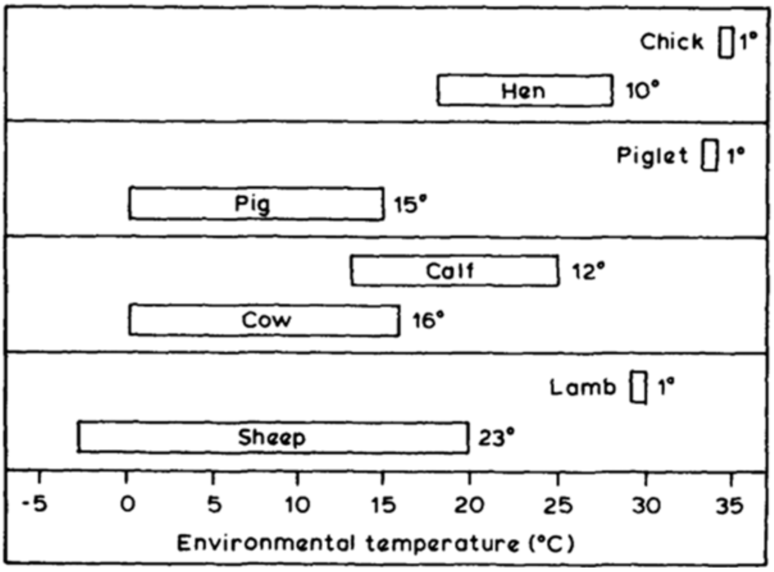

Fig. 4.8 Temperature zones in which farm animals perform effectively. Numbers alongside *boxes* indicate temperature range (Bianca 1976)

than adults (Fig. 4.8). A rise in summer temperatures, especially in regions with a continental climate characterized today by summer temperatures near the threshold tolerated by livestock (such as the South Central USA and USSR), could be detrimental to production (Squire and Unsworth 1988).

4.4 Varying Precipitation Patterns

An increase in temperatures will trigger increased demand for water for evapotranspiration by crops and natural vegetation and will lead to more rapid depletion of soil moisture. This scenario, combined with changes in rainfall patterns, may lead to more frequent crop failures. Agriculture will be affected by increased evaporative demand, changes in the amount of rainfall, and variations in river runoff and groundwater recharge, the two sources of water for irrigation.

Water is vital to plant growth, so varying precipitation patterns have a significant impact on agriculture. As over 80 % of total agriculture is rain-fed, projections of future precipitation changes often influence the magnitude and direction of climate impacts on crop production. The impact of global warming on regional precipitation is difficult to predict, owing to strong dependencies on changes in atmospheric circulation, although there is increasing confidence in projections of a general increase in high-latitude precipitation, especially in winter, and an overall decrease in many parts of the tropics and subtropics (IPCC 2007). These uncertainties project different signs of precipitation change averaged over all croplands, even though there is agreement in the sign of change in some regions. One scenario which predicts an overall increase in precipitation shows large increases in southern USA and India but also significant decreases in the tropics and subtropics. The other scenario also shows the decreases in the low latitudes but without significant increases in India.

Changes in seasonal precipitation may be more relevant to agriculture than annual mean changes. In India, climate models generally project a decrease in dry season precipitation and an increase during the rest of the year including the monsoon season, but still with a large inter-model spread (Christensen et al. 2007).

Precipitation is not the only influence on water availability. Increasing evaporative demand owing to rising temperatures and longer growing seasons could increase crop irrigation requirements globally by between 5 and 20 %, or possibly more, by the 2070s or 2080s, but with large regional variations – Southeast Asian irrigation requirements could increase by 15 %. Regional studies project increasing irrigation demand in the Middle East and North Africa. However, decreased requirements are projected in China. Clearly these projections also depend on uncertain changes in precipitation.

Precipitation, being the primary source of soil moisture, is probably the most important factor determining the productivity of crops. While global climate models predict an overall increase in mean global precipitation, their results also show the potential for changed hydrological regimes (either drier or wetter) in most places. A change in climate can cause changes in total seasonal precipitation, its within-season pattern, and its between-season variability. For crop productivity, a change in the pattern of precipitation events may be even more important than a change in the annual total. The water regime of crops is also vulnerable to a potential rise in the daily rate and altered seasonal pattern of evapotranspiration, brought on by warmer temperature, drier air, or windier conditions.

Drought conditions may also be brought on by lower amounts of precipitation falling as snow and by earlier snow melt. In arid regions, such as the Sacramento River Basin in California, these effects may reduce subsequent river discharge and irrigation water supplies during the growing season. Episodes of high relative humidity, frost, and hail can also affect yield and the quality of corn and other grains and fruits and vegetables.

Interannual variability of precipitation is a major cause of variation in crop yields and yield quality. During the 1930s, severe droughts reduced US Great Plains yields of wheat and corn by as much as 50 %. By reducing vegetative cover, droughts exacerbate wind and water erosion, thus affecting future crop productivity.

Crop yields are most likely to suffer if dry periods occur during critical developmental stages such as reproduction. In most grain crops, flowering, pollination, and grain filling are especially sensitive to water stress. Management practices offer strategies for growing crops in water scarce conditions. For example, the effects of drought can be avoided by early planting of cultivars with rapid rates of development. Fallowing and weed control can also help to conserve moisture in the soil.

Heat stress and drought stress often occur simultaneously, the one contributing to the other. These conditions are often accompanied by high solar irradiance and high winds. When crops are subjected to drought stress, their stomata close. Such closure reduces transpiration and, consequently, raises plant temperatures.

Excessively wet years, on the other hand, may cause yield declines due to water logging and increased pest infestations. High soil moisture in humid areas can also hinder field operations. Intense bursts of rainfall may damage younger plants and promote water logging of standing crops with ripening grain as well as soil erosion. The extent of crop damage depends on the duration of precipitation and flooding, crop developmental stage, and air and soil temperatures. The costs of drying corn are higher under wetter climate regimes.

In most of the tropical and equatorial regions of the world, and across large areas outside the tropics, the yield of agricultural crops is limited more by the amount of water received by and stored in the soil than by air temperature. Even in the high mid-latitudes such as in southern Scandinavia, too little rain can restrict growth of cereal crops during the summer when evapotranspiration exceeds rainfall. In all these areas, the amount of dry matter a crop produces is roughly proportional to the amount of water it transpires (Monteith 1981). This, in turn, is affected by the quantity of rainfall but not in a straightforward manner: it also depends on how much of the rainfall is retained in the soil, how much is lost through evaporation from the soil surface, and how much remains in the soil that the crop cannot extract.

The amount of water transpired by the crop is also determined by air humidity, with generally less dry matter produced in a drier atmosphere (Monteith 1981). Thus, changes in both rainfall and air humidity would be likely to have significant effects on crop yields.

Reliability of rainfall, particularly at critical phases of crop development, can explain much of the variation in agricultural potential in tropical regions. Thus, many schemes used to map zones of agricultural potential around the world have adopted some form of ratio of rainfall to potential evaporation, *r*/*E*o, to delimit moisture-availability zones, which are then overlaid on temperature and soil maps to indicate agroecological zones (Sombroeck et al. 1982). The regions are distinguished largely on the basis of the length of growing season determined by the *r*/*E*o ratio. In Kenya, for example, average plant biomass is estimated to vary by more than an order of magnitude between agroclimatic zones that lie within 100 km of each other (Akong'a et al. 1988). These are characterizations of the effect of differences in average rainfall on agricultural potential, but it is important to note that a high degree of interannual variability of rainfall, particularly in the drier zones, can lead to very marked variation in crop yield between wet and dry years, so that changes in rainfall over time as well as over space are also likely to have a similar effect on crop yields.

A strongly positive relationship between rainfall and crop yield is generally found in the major mid-latitude cereal-exporting regions of the world, such as the US Great Plains and Soviet Ukraine. For example, in the dry steppe zone of the Volga Basin (USSR), a 0.5 or 1 °C warming, with no change in rainfall, is estimated to have little effect on spring wheat yields, while a 20 % decrease in rainfall (at current temperatures) could reduce yields by more than a tenth.

Relatively few studies have been made of the combined effects of possible changes in temperature and rainfall on crop yields and those that have are based on a variety of different methods. However, a recent review of results from about ten studies in North America and Europe noted that warming is generally detrimental to yields of wheat and maize in these mid-latitude core cropping regions. With no change in precipitation (or radiation), slight warming (+1 °C) might decrease average yields by about 5 + 4 %, and a 2 °C warming might reduce average yields by about 10 + 7 % (Edwards and Walker 1983). In addition, reduced precipitation might also decrease yields of wheat and maize in these bread-basket regions. A combination of increased temperatures (+2 °C) and reduced precipitation could lower average yields by over a fifth.

The large-scale public surface irrigation systems built during the green revolution dominated the landscape until the early 1980s and had a profound impact on the flow of many rivers. Over the last 30 years, private investments, stimulated by the availability of cheap pumps and well-drilling capacity, have been directed to tapping groundwater. Consequently, aquifers are being depleted in countries with key agricultural production systems, including China, India, and the USA.

The role climate change will play with regard to water in agriculture must be considered in context of rapid increases in water withdrawals, the degradation of water quality, and the competition for water at all levels.

Changes in the distribution of precipitation, with longer periods between rainfall events and more intense precipitation, are expected everywhere. This may lead to increased occurrence of extreme weather events, including floods and droughts. Dry spells, the short periods of rainfall deficit during the cropping season, are expected to increase in duration and frequency. This will directly affect soil moisture and the productivity of rainfed crops. Such changes will be felt mostly in areas already subject to climate variability, such as in the semiarid and subhumid areas of sub-Saharan Africa and South Asia, where, in the absence of alternative sources of water, the risk of increased frequency of crop failures is high.

Reductions of rainfall in arid and semiarid areas will translate into a much larger reduction in river runoff (in relative terms). In Cyprus, for example, analyses have shown that a 13 % reduction in rainfall translates into a 34 % reduction in runoff (Faurès et al. 2010). In rivers receiving their water from glacier or snow melt (about 40 % of the world's irrigation is supported by flows originating in the Himalayas), the timing of flows will change, with high flows occurring earlier in the year. However, the mean annual runoff may be less affected.

The impact of climate change on groundwater recharge will be reduced in arid and semiarid areas, where runoff will decline (Table 4.10) (Turral et al. 2011). In arid and semiarid areas, climate change will place additional burdens on already stretched water resources. However, agriculture will first need to respond to the challenges posed by increasing human pressures on these resources.

Finally, the expected rise in sea levels will affect agriculture in coastal areas, particularly river deltas. Higher sea levels combined with upstream changes (variations in runoff distribution, more frequent floods) will result in an increased incidence of floods and saltwater intrusion in estuaries and aquifers.

4.4.1 Changes in Hydrological Regimes and Shifts in Precipitation Patterns

The hydrological regimes in which crops grow will surely change with global warming. While all GCMs predict increases in mean global precipitation (because a warmer atmosphere can hold more water vapor), which are not uniformly distributed, decreases are forecast in some regions. The crop water regime may further be affected by changes in seasonal precipitation, within-season pattern of precipitation, and interannual variation of precipitation. Increased convective rainfall is predicted to occur, particularly in the tropics, caused by stronger convection cells and more moisture in the air.

Too much precipitation can cause disease infestation in crops, while too little can be detrimental to crop yields, especially if dry periods occur during critical development stages. For example, moisture stress during the flowering, pollination, and grain-filling stages is especially harmful to maize, soybean, wheat, and sorghum.

The amount and availability of water stored in the soil, a crucial input to crop growth, will be affected by changes in both the precipitation and seasonal and annual evapotranspiration regimes. Some GCMs predict mid-continental

Table 4.10 Influence of climate change and development on water supply and demand (Turral et al. 2011)

Elements of the water cycle	Impact from	
	Development activities	Climate change
Annual precipitation	No or minor impact	Expected to increase globally during the twenty-first century, with potentially great spatial variations
Interannual variations in precipitations	No impact	Expected to increase everywhere
Seasonal variability of rainfall	No impact	Expected to increase everywhere
Soil moisture stress (droughts)	Limited impact: some agricultural practices can deplete soil moisture faster than natural vegetation	Moisture stress to generally increase as a result of increasing variability of rainfall distribution (longer periods without rain) and increasing temperatures
Floods	Moderate impact: flood intensity and impact can be exacerbated by changes in land use and unplanned development in alluvial plains	Increased as a result of increasing frequency and intensity of extreme rainfall events
Snow and glacier melt	Limited impact through deposit of pollutants and change in the reflecting power of the surface (albedo)	Rising temperatures lead to accelerated snow and glacier melt with initial increases in river flow followed by decreases
River discharge	High impact in water scarce areas, where reservoir construction and water diversion for agriculture and other uses are modifying runoff regimes and reducing annual flow. Large-scale water conservation measures also have an impact on river discharge	Increased variability as a result of changes in rainfall patterns. Changes in snow and glacier melt induce changes in seasonal patterns of runoff. Changes in annual runoff expected to vary from region to region
Groundwater	High impact: large-scale development of groundwater resources in many regions is already threatening the sustainability of aquifers in many dry areas	Varies as a function of changes in rainfall volumes and distribution. Impact is complex, with floods contributing to increasing recharge and droughts leading to increased pumping
Evapotranspiration	Limited impact in agriculture: some crops have higher evapotranspiration rates than natural systems, other less	Increases as a function of temperature increases
Water quality (in rivers, lakes, and aquifers)	High impact from pollution in highly developed areas	Moderate impact through temperature increases
Salinity in rivers and aquifers	High impact from water withdrawal in highly developed areas (mostly in arid regions)	Potentially high impact where sea water level rise combines with reduced runoff and increased withdrawal

drying in the Northern Hemisphere (Kellogg and Zhao 1988), while other GCM suggest that the rise in potential evapotranspiration will exceed that of rainfall, resulting in drier regimes throughout the tropics and low to mid-latitudes (Rind et al. 1990). Because the soil moisture processes are represented so crudely in the current GCMs, however, it is difficult to associate much certainty with these projections (IPCC 1990).

Global climate change is likely to exacerbate the demand for irrigation water (Adams et al. 1990). Higher temperatures, increased evaporation, and yield decreases contribute to this projection. However, supply of needed irrigation water under climate change is uncertain. Where water supplies are diminishing, such as the Ogallala Aquifer in the USA, extra demand might require that some land be withdrawn from irrigation (Rosenzweig 1990).

4.5 Soil Fertility and Erosion

The soil system responds to short-term events such as rainfall and also undergoes long-term changes such as physical and chemical weathering due to climate change. The potential impacts on soil health due to climate change would be in the organic matter supply, temperature regimes, hydrology, and salinity. Soil carbon levels are expected to decrease due to decreased net primary production. Any gains by the increased plant water-use efficiency, due to elevated CO_2, are likely to be outweighed by increased carbon mineralization after episodic rainfall and reduced annual and growing season rainfall. The quality of soil organic matter may also shift where the more inert components of the carbon pool prevail. The increase in soil temperature increases N mineralization, but its availability may decrease due to increased gaseous losses through processes such as volatilization and denitrification.

No comprehensive study has yet been made of the impact of possible climatic changes on soils. Higher temperatures could increase the rate of microbial decomposition of organic matter, adversely affecting soil fertility in the long run (Hillel and Rosenzweig 1989). But increases in root biomass resulting from higher rates of photosynthesis could offset these effects. Higher temperatures could accelerate the cycling of nutrients in the soil, and more rapid root formation could promote more nitrogen fixation. But these benefits could be minor compared to the deleterious effects of changes in rainfall. For example, increased rainfall in regions that are already moist could lead to increased leaching of minerals, especially nitrates. In the Leningrad region of the USSR, a one-third increase in rainfall (which is consistent with the GISS $2xCO_2$ scenario) is estimated to lead to falls in soil productivity of more than 20 %. Large increases in fertilizer applications would be necessary to restore productivity levels (Pitovranov et al. 1988).

Decreases in rainfall, particularly during summer, could have a more dramatic effect, through the increased frequency of dry spells, leading to increased proneness to wind erosion. Susceptibility to wind erosion depends in part on cohesiveness of the soil (which is affected by precipitation effectiveness) and wind velocity. The only study completed on this subject suggests that in Saskatchewan (on the Canadian prairies) the frequency of moderate and extreme droughts would increase threefold under a $2xCO_2$ climate if mean May–August temperatures increased by 3.5 °C and precipitation increased by 9–14 %, which is consistent with the GISS $2xCO_2$ climate. They would increase 13-fold if increases in temperature are not accompanied by increases in precipitation.

Soil temperature affects the rates of organic matter decomposition and release of nutrients. At high temperatures, though nutrient availability will increase in the short term, in the long run organic matter content will diminish, resulting in a decline in soil fertility. Estimated changes in the potential for wind erosion under the latter scenario vary from +24 to +29 % (Williams et al. 1988).

4.5.1 Soils

Climate change will also have an impact on the soil, a vital element in agricultural ecosystems. Higher air temperatures will cause higher soil temperatures, which should generally increase chemical solution reaction rates and diffusion-controlled reactions (Buol et al. 1990). Solubilities of solid and gaseous components may either increase or decrease, but the consequences of these changes may take many years to become significant (Buol et al. 1990). Furthermore, higher temperatures will accelerate the decay of soil organic matter, resulting in release of CO_2 to the atmosphere and decrease in carbon/nitrogen ratios, although these two effects should be offset somewhat by the greater root biomass and crop residues resulting from plant responses to higher CO_2.

In temperate countries where crops are already heavily fertilized, there will probably be no major changes in fertilization practices, but alterations in timing and method (e.g., careful adjustment of side-dress applications of nitrogen during vegetative crop growth) are expected with changes in temperature and precipitation regimes (Buol et al. 1990). In tropical countries, where fertilization level is not always adequate, the need for fertilization will probably increase.

Sea-level rise, another predicted effect of global warming, will cause increased flooding, saltwater intrusion, and rising water tables in agricultural soils located near coastlines. This is particularly crucial in tropical countries such as Bangladesh, with large agricultural regions and high rural population located near current sea level.

4.5.2 Erosion and Fertility

The warmer atmospheric temperatures observed over the past decades are expected to lead to a more vigorous hydrological cycle, including more extreme rainfall events. Erosion and soil degradation is more likely to occur. Soil fertility would also be affected by global warming. However, because the ratio of carbon to nitrogen is a constant, a doubling of carbon is likely to imply a higher storage of nitrogen in soils as nitrates, thus providing higher fertilizing elements for plants, providing better yields. The average needs for nitrogen could decrease and give the opportunity of changing often costly fertilization strategies.

Due to the extremes of climate that would result, the increase in precipitations would probably result in greater risks of erosion while at the same time providing soil with better hydration, according to the intensity of the rain. The possible evolution of the organic matter in the soil is a highly contested issue: while the increase in the temperature would induce a greater rate in the production of minerals, lessening the soil organic matter content, the atmospheric CO_2 concentration would tend to increase it.

4.5.3 Salinity

Salinity is also a serious problem that reduces growth and productivity of vegetable crops in many salt-affected areas. It is estimated that about 20 % of cultivated lands and 33 % of irrigated agricultural lands worldwide are afflicted by high salinity (Ghassemi et al. 1995). In addition, the salinized areas are increasing at a rate of 10 % annually; low precipitation, high surface evaporation, weathering of native rocks, irrigation with saline water, and poor cultural practices are the major contributors to the increasing soil salinity. In spite of the physiological cause of ion toxicity, water deficit, and/or nutritional imbalance, high salinity in the root area sternly inhibits normal plant growth and development, resulting in reduced crop productivity or total crop failure (Ghassemi et al. 1995).

Young seedlings and plants at anthesis appear to be more sensitive to salinity stress than at the mature stages (Lutts et al. 1995). Onions are sensitive to saline soils, while cucumbers, eggplants, peppers, beet palak, and tomatoes are moderately sensitive. One of the most effective ways to overcome salinity problems is the use of tolerant species and varieties (Yilmaz et al. 2004). The response of plants to increasing salt application may differ significantly among plant species as a function of their genetic tolerance.

4.6 Extreme Weather Events

Most scientists believe that the warming of the climate will lead to more extreme weather patterns (heat waves, droughts, strong winds, and heavy rains) such as:

- More hurricanes and drought.
- Longer spells of dry heat or intense rain (depending on where you are in the world).
- Scientists have pointed out that Northern Europe could be severely affected with colder weather if climate change continues, as the arctic begins to melt and send fresher waters further south. It would effectively cut off the Gulf Stream that brings warmth from the Gulf of Mexico, keeping countries such as Britain warmer than expected.
- In South Asia, the Himalayan glaciers could retreat, causing water scarcity in the long run.

While many environmental groups have been warning about extreme weather conditions for a few years, the World Meteorological Organization announced in July 2003 that "Recent scientific assessments indicate that, as the global temperatures continue to warm due to climate change, the number and intensity of extreme events might increase."

The frequency of extreme weather events, such as droughts and floods, is predicted to increase. According to the IPCC, the impacts of climate change and associated costs will fall disproportionately on developing countries and may undermine the achievement of the global goals of reducing poverty and safeguarding food security (IPCC 2001). The 2011 drought in the Horn of Africa, which threatened 12 million people with malnutrition, disease, and loss of livelihoods, is a recent example of an extreme weather event. As such events become more frequent, the number of vulnerable or directly affected people will increase.

The balance between profit and loss in commercial farming often depends on the relative frequencies of favorable and adverse weather; for example, on the Canadian prairies, a major constraint on profitable wheat production is related to the probability of the first autumn frost occurring before the crop matures (Robertson 1970).

Changes in rainfall could have a similarly magnified impact. For example, if mean rainfall in the Corn Belt in March (which is about 100 mm) decreased by 10 % (an amount projected by some GCMs under a 2xCO_2 climate), this would raise the probability of less than 25 mm being received by 46 %. For cattle, crops, and trees, a 1 % reduction in rainfall could mean that drought-related yield losses increase by as much as a half (Waggoner 1983).

Sequential extremes can affect yields and disease patterns. Droughts, followed by intense rains, for example, can have an impact on soil water absorption, increasing the potential for flooding that creates conditions favoring fungal infestations of leaves, roots, and tuber crops. Prolonged anomalous periods – such as the 5 years of El Niño conditions between 1990 and 1995 – can also have destabilizing affects on agriculture.

Sequential extremes, along with altered timing of seasons, may also decouple long-evolved relationships among species (e.g., predator/prey) essential for controlling pests and pathogens as well as populations of plant pollinators.

Strong winds can cause leaf and limb damage, as well as "sand blasting" of the soil against the foliage. Heavy rains that often result in flooding can also be detrimental to crops and to soil structure. Most plants cannot survive in prolonged waterlogged conditions because the roots need to breathe. In addition, flooding can erode top soil from prime growing areas, resulting in irreversible habitat damage. Heavy winds combined with rain (from events such as hurricanes and tornadoes) can down large trees and damage houses, barns, and other structures involved in agricultural production.

Considerations of the potential impacts of climate change on agriculture should, therefore, be based not only on the mean values of expected climatic parameters but also on the probability, frequency, and severity of possible extreme events.

4.6.1 Extreme Temperatures

Meteorological records suggest that heat waves became more frequent over the twentieth century, and while individual events cannot be attributed to climate change, the change in probability of a heat wave can be attributed. Europe experienced a particularly extreme climate event during the summer of 2003, with average temperatures 6 °C above normal and precipitation deficits of up to 300 mm. A record crop yield loss of 36 % occurred in Italy for corn grown in the Po Valley where extremely high temperatures prevailed (Ciais et al. 2005). It is estimated that such summer temperatures in Europe are now 50 % more likely to occur as a result of anthropogenic climate change. In 1972, extremely high summer average temperature in the former Soviet Union (USSR) contributed to widespread disruptions in world cereal markets and food security.

Changes in short-term temperature extremes can be critical, especially if they coincide with key stages of development. Only a few days of extreme temperature (greater than 32 °C) at the flowering stage of many crops can drastically reduce yield. Both growth and developmental processes, however, exhibit temperature optima. In the short term, high temperatures can affect enzyme reactions and gene expression. In the longer term, these will impact on carbon assimilation and thus growth rates and eventual yield. The plants experience warming periods as independent events, and critical temperatures of 35 °C for a short period around anthesis had severe yield-reducing effects. Although groundnut is grown in semiarid regions which regularly experience temperatures of 40 °C, if after flowering the plants are exposed to temperatures exceeding 42 °C, even for short periods, yield can be drastically reduced. Maize exhibits reduced pollen viability for temperatures above 36 °C. Rice grain sterility is brought on by temperatures in the mid-30s, and similar temperatures can lead to the reverse of the vernalizing effects of cold temperatures in wheat. Increases in temperature above 29 °C for corn, 30 °C for soybean, and 32 °C for cotton negatively impact on yields in the USA.

Extremely dry summers (of a kind that can cause severe food shortage in a given region) occur at present with a probability of $P = 0.1$. The return period of the occurrence of a single drought is, therefore, 10 years, while the return period for the occurrence of two successive droughts is 100 years (assuming a normal distribution of frequencies). A change in climate can lead to a change in P, either through altered variability which will change P directly or through a change in mean conditions that must also change P if drought is judged relative to an absolute threshold. Alternatively, P may change through changes in some critical impact threshold as a result of altered land use, increasing population pressure, and so forth. If P becomes 0.2, then the return period of a single drought is halved to 5 years. The return period for two successive droughts, however, is reduced by a factor of four to only 25 years (Wigley 1985). Thus, not only is agriculture often sensitive to climatic extremes, but the risk of climatic extremes may be very sensitive to relatively small changes in the mean climate.

The impact on agriculture from climatic change can be expected to stem from the effects of extreme events. Consider first the significantly increased costs resulting from increased frequency of extremely hot days causing heat stress in crops. In the central USA, the number of days with temperatures above 35 °C, particularly at the time of grain filling, has a significant negative effect on maize and wheat yields (Thompson 1975). The incidence of these very hot days is likely to increase substantially with a quite small increase in mean temperature. For example, in Iowa, in the US Corn Belt, an increase in mean temperature of only 1.7 °C may bring about a threefold increase in the probability of five consecutive days with a maximum temperature over 35 °C (Mearns et al. 1984). At the southern edge of the Corn Belt, where maize is already grown near its maximal temperature-tolerance limit, such an increase could have a very deleterious effect on yield.

The increase in risk of heat stress on crops and livestock due to global warming could be especially important in tropical and subtropical regions where temperate cereals are currently grown near their limit of heat tolerance. For example, in northern India, where GCM experiments indicate an increase in mean annual temperature of about 4 °C, wheat production might no longer be viable.

An important additional effect of warming, especially in temperate regions, is likely to be the reduction of winter chilling (vernalization). Many temperate crops require a period of low temperatures in winter either to initiate or to accelerate the flowering process. Low vernalization results in low flower-bud initiation and, ultimately, reduced yields. A 1 °C warming could reduce effective winter chilling by between 10 and 30 % (Salinger 1989).

Relatively small changes in mean temperature can result in disproportionately large changes in the frequency of extreme events. Des Moines, Iowa, in the heart of the Corn Belt, currently experiences fewer than 20 days above 90 °F; this would double with a mean warming of 3.6 °F. For a similar level of warming, Phoenix, Arizona, where irrigated cotton is grown, would have 120 days above 100 °F, instead of the 90 odd days in the present climate.

4.6.2 Drought

Droughts have been occurring more frequently because of global warming, and they are expected to become more frequent and intense in Africa, Southern Europe, the Middle East, most of the Americas, Australia, and Southeast Asia (Fraser et al. 2013). Their impacts are aggravated because of increased water demand, population growth, urban expansion, and environmental protection efforts in many areas (Rosenzweig 2007). Droughts result in crop failures and the loss of pasture-grazing land for livestock (Rosenzweig 2007).

Droughts are damaging because of the long-term lack of water available to the plants. Droughts have been responsible for some of the more serious famines in the world, although sociological factors are also important. Heat waves can cause extreme heat stress in crops, which can limit yields if they occur during certain times of the plants' life cycle (pollination, pod or fruit set). Also, heat waves can result in wilted plants (due to elevated transpiration rates) which can cause yield loss if not counteracted by irrigation.

Globally, the areas sown for the major crops of barley, maize, rice, sorghum, soybean, and wheat have all seen an increase in the percentage of area affected by drought as defined in terms of the Palmer Drought Severity Index (PDSI) since the 1960s, from approximately 5–10 % to approximately 15–25 %. The MOHC climate model simulates the proportion of the land surface under drought to have increased from 20 to 28 % over the twentieth century.

Present-day mean yield reduction rate (YRR) values are diagnosed as ranging from 5.82 % (rice) to 11.98 % (maize). By assuming the linear relationship between the drought risk index and YRR holds into the future, it is estimated that drought-related yield reductions would increase by more than 50 % by 2050 for the major crops.

A drought in livestock grazing systems (Fig. 4.9) reduces the availability of water and grass – both directly and indirectly because as the watering points are reduced, some pastures are no more accessible – and so increases the demand

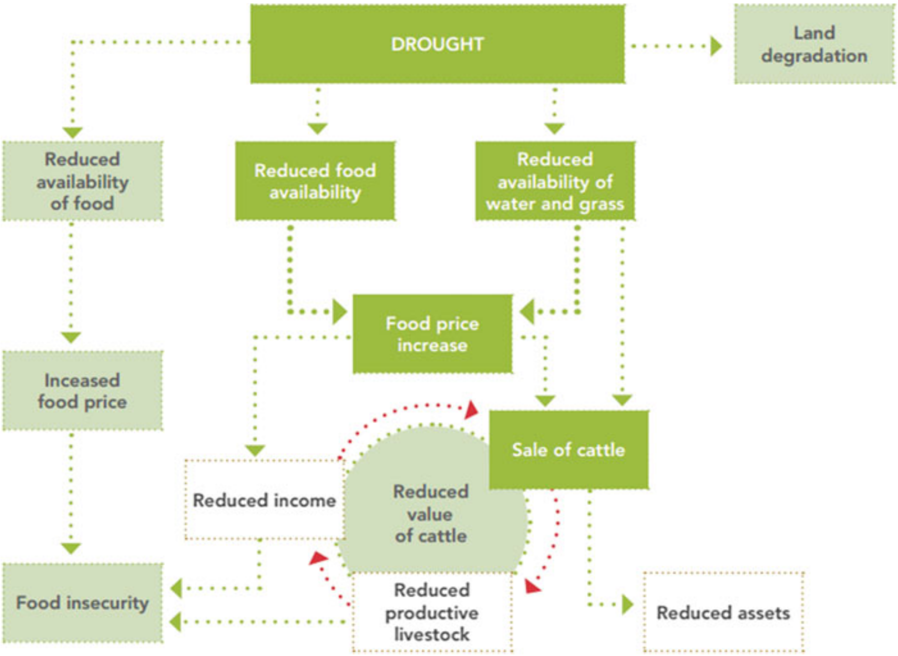

Fig. 4.9 Impacts of drought on livestock

for feed at the very moment when there is less feed available. Increased demand drives a feed price increase, which forces livestock owners to sell their cattle. Massive sales while there is a reduced demand push down cattle prices, forcing livestock owners to sell even more to buy feed. These effects on prices reduce farm and household income and assets. Moreover, they reduce the value of assets (livestock) and productive capital for the future. Prolonged or repeated drought also has long-lasting degrading effects on land. The combination of drought and overgrazing, particularly near watering points, destroys the vegetal cover and increases soil erosion.

4.6.3 Heavy Rainfall and Flooding

Food production can also be impacted by too much water. Heavy rainfall events leading to flooding can wipe out entire crops over wide areas, and excess water can also lead to other impacts including soil water logging, anaerobicity, and reduced plant growth. Indirect impacts include delayed farming operations. Agricultural machinery may simply not be adapted to wet soil conditions. In a study looking at the impacts of current climate variability, the heavy rainfall in August was linked to lower grain quality which leads to sprouting of the grain in the ear and fungal disease infections of the grain. This was shown to affect the quality of the subsequent products such that it influenced the amount of milling wheat that was exported from the UK. The proportion of total rain falling in heavy rainfall events appears to be increasing, and this trend is expected to continue as the climate continues to warm. A doubling of CO_2 is projected to lead to an increase in intense rainfall over much of Europe. In the higher-end projections, rainfall intensity increases by over 25 % in many areas important for agriculture.

Crop production is often limited during the rainy season due to excessive moisture brought about by heavy rains. Most vegetables are highly sensitive to flooding, and genetic variation with respect to this character is limited, particularly in tomato and early cauliflower. In general, the damage to vegetables by flooding is due to reduction of oxygen in the root zone, which inhibits aerobic processes. Flooded tomato plants accumulate endogenous ethylene that causes damage to the plants (Drew 1979). The rapid development of epinastic growth of leaves is a characteristic response of tomatoes to waterlogged conditions, and the role of ethylene accumulation has been implicated (Kawase 1981). The severity of flooding symptoms increases with rising temperatures; rapid wilting and death of tomato plants is usually observed following a short period of flooding at high temperatures (Kuo et al. 1982).

4.6.4 Tropical Storms

Climate models do not do a good job of predicting how extreme weather events might change under global warming. For example, models do not agree on whether the number of hurricanes in a warmer world would be more or less than current values, but scientists generally feel that the strength of the largest hurricanes will increase. The length of the hurricane season could also increase. Observational changes in the number of tornadoes per year we see now may be due to increases in the number of people watching the skies and the growth of urban areas rather than any strict climate changes. It is not clear if observed changes in extreme weather events we see now are part of long natural cycles, or if they are in response to climate change. Nonetheless, all of these events can be detrimental to crop growth. The most vulnerable agricultural regions for tropical cyclones are found, among others, in the USA, China, Vietnam, India, Bangladesh, Myanmar, and Madagascar.

Both societal and economic implications of tropical cyclones can be high, particularly in developing countries with high population growth rates in vulnerable tropical and subtropical regions. This is particularly the case in the North Indian Ocean, where the most vulnerable people live in the river deltas of Myanmar, Bangladesh, India, and Pakistan; here population growth has resulted in increased farming in

Table 4.11 Selected tropical cyclones of the past decade and their agricultural impacts

Date	Location	Cyclone name	Agricultural impact
Feb–Apr 2000	Madagascar	Eline, Gloria (Feb), Hudah (Apr)	Combined losses owing to three cyclones: 149,441 ha rice (7 % of annual production), 5,000 ha maize, 155,000 ha cereals (FAO 2000)
2006–2007	Madagascar	Bondo (Dec 2006), Clovis (Jan 2007), Favio (Jan 2007), Gamede (Feb 2007), Indlala (Mar 2007)	Combined losses: 90,000 ha of crop (IFRC 2007); 80 % of vanilla production lost to Indlala alone (FAO 2007)
2007	Mozambique	Favio	Thousands of hectares of crop destroyed (FAO 2007)
Nov 2007	Bangladesh	Sidr	1.6 million acres of cropland damaged; >25 % winter rice crop destroyed (United Nations 2007)
May 2008	Irrawaddy Delta, Myanmar (Burma)	Nargis	Estimated 4 m storm surge inundated coastal areas and regions up to 40 km inland. Soil salination made 50,000 acres of rice cropland now unfit for planting. Loss of rice seed, fertilizers, farm machinery, and valuable land threatened the winter 2008/2009 rice crop including exports to neighboring countries (FAO 2009)

coastal regions most at risk from flooding. In 2007, cyclone Sidr hit Bangladesh costing 3,500 lives, and in 2008 cyclone Nargis caused 130,000 deaths in Myanmar. The agricultural impacts of these and other recent cyclones are shown in Table 4.11.

Although many studies focus on the negative impacts, tropical cyclones can also bring benefits. In many arid regions in the tropics, a large portion of the annual rain comes from cyclones. It is estimated that tropical cyclones contribute to 15–20 % of South Florida's annual rainfall, which can temporarily end severe regional droughts. Examples of such storms are hurricane Gabrielle (2001) and tropical storm Fay (2008), which provided temporary relief from the 2000–2001 and 2006–2009 droughts, respectively. As much as 30 cm of rainfall was recorded in some regions from tropical storm Fay, without which regions would have faced extreme water shortage, wildfires, and potential saltwater intrusion into coastal freshwater aquifers. Tropical cyclones can also help replenish water supplies to inland regions: cyclone Eline, which devastated agriculture in Madagascar in February 2000, later made landfall in South Africa and contributed significantly to the rainfall in the semidesert region of southern Namibia.

Climate modeling studies contributing to the IPCC's Fourth Assessment Report (AR4) suggest tropical cyclones may become more intense in the future with stronger winds and heavier precipitation.

4.7 Livestock Production

Climate change poses serious threats to livestock production. Increased temperatures, shifts in rainfall distribution, and increased frequency of extreme weather events are expected to adversely affect livestock production and productivity around the world. These adverse impacts can be the direct result of increased heat stress and reduced water availability. Indirect impacts can result from the reduced quality and availability of feed and fodder, the emergence of livestock diseases, and greater competition for resources with other sectors (Thornton and Gerber 2010).

The effects of climate change on livestock are likely to be widespread. The most serious impacts

Table 4.12 Direct and indirect impacts of climate change on livestock production systems

	Grazing system	Non-grazing system
Direct impacts	Increased frequency of extreme weather events	Change in water availability (may increase or decrease, according to region)
	Increased frequency and magnitude of droughts and floods	Increased frequency of extreme weather events (impact less acute than for extensive system)
	Productivity losses (physiological stress) due to temperature increase	
	Change in water availability (may increase or decrease, according to region)	
Indirect impacts	Agroecological changes and ecosystem shifts leading to:	Increased resource prices (e.g., feed, water, and energy)
	Alteration in fodder quality and quantity	Disease epidemics
	Change in host–pathogen interaction resulting in an increased incidence of emerging diseases	Increased cost of animal housing (e.g., cooling systems)
	Disease epidemics	

are anticipated in grazing systems because of their dependence on climatic conditions and the natural resource base and their limited adaptation opportunities (Aydinalp and Cresser 2008). Impacts are expected to be most severe in arid and semiarid grazing systems at low latitudes, where higher temperatures and lower rainfall are expected to reduce yields on rangelands and increase land degradation (Hoffman and Vogel 2008).

The direct impacts of climate change are likely to be more limited in non-grazing systems mostly because the housing of animals in buildings allows for greater control of production conditions (Thornton and Gerber 2010). In non-grazing systems, indirect impacts from lower crop yields, feed scarcity, and higher energy prices will be more significant. Climate change could lead to additional indirect impacts from the increased emergence of livestock diseases, as higher temperatures and changed rainfall patterns can alter the abundance, distribution, and transmission of animal pathogens (Baylis and Githeko 2006) (Table 4.12).

The main effects of climate change on livestock from increased temperature and decreased precipitation is distress, but because livestock do not have the same limitations as crops, there are potential benefits to expanding acreage.

The increasing temperatures can have varying effects, depending on when they occur. Warmer conditions in the summer can lead to stress on range and housed livestock since dry pastures, poor hay, and feed production and shortages of water all lead to worse conditions for cattle. On the other hand, increased temperatures during the winter months can reduce the cold stress experienced by livestock remaining outside as well as reduce the energy requirements to heat the facilities of those animals inside.

Crops required class 3 or better land to produce acceptable yield, while the pastures does not have the same restrictions to produce acceptable yield. The increased temperature would have a positive effect on the growth of the pasture and provide better feed for livestock. This assumes that the pastures are in areas where moisture is not a critical issue.

Water resources are critical to a successful livestock operation. All livestock operations require good quality drinking water, and without it livestock will not survive. As with crops, diseases and insects could have an adverse effect on much of the livestock industry. Insects and diseases that livestock is unaccustomed to could move into the production area. Secondary effects such as dust storms and wind erosion also factor into the worsening conditions for livestock.

Livestock is more resistant to climate change than crops because of its mobility and access to feed. Livestock production could be one of the key methods for farmers to adapt to climate change through diversification of their farming mix.

4.8 Fisheries and Aquaculture

The impacts of the accumulation of GHGs in the atmosphere and water relate to a number of physical phenomena including gradual changes in water temperature, acidification of water bodies, changes in ocean currents, and rising sea levels. These physical changes affect ecological functions within aquatic systems and the frequency, intensity, and location of extreme weather events (Cochrane et al. 2009). A range of impacts on fisheries and aquaculture, both direct and indirect, can be expected. These are illustrated in Table 4.13.

Ecosystem productivity is likely to be reduced in most tropical and subtropical oceans, seas, and lakes. In high-latitude ecosystems, productivity is likely to increase. Physiological and behavioral processes of fish and the organisms they feed on will also be affected. The impacts, both positive and negative, will depend on the region and latitude. There is increasing evidence that global warming is already modifying the distribution of marine species. Warmwater species are being displaced towards the poles and experiencing changes in their size and the productivity of their habitats.

Table 4.13 Potential climate change impact pathways for fisheries and aquaculture

GHG accumulation and global warming changes	Areas affected	Impacts
• Ocean currents • El Niño Southern • Oscillation • Sea-level rise • Rainfall • River flows • Lake levels • Thermal structure • Storm severity • Storm frequency • Acidification	Production ecology	Species composition, production and yield, distribution and seasonality, disease and other disruptions, coral bleaching, calcification
	Fishing, aquaculture, and postharvest operations	Safety and security, efficiency and costs, infrastructure security
	Communities and livelihoods	Loss and damages to assets, risks to life and health, vulnerability and confidence, displacement and conflict
	Wider society and economy	Costs of mitigation and adaptation, social and market impacts, water, and other resource

4.8.1 Predicted Changes in Fisheries Catch Potential During 2005–2055 Under a Higher GHG Emissions Scenario

Tropical countries could face up to a 40 % drop in catch potential. High-latitude regions could enjoy as much as a 30–70 % increase in catch potential.

How would the current top fishing countries fare under this scenario? The model predicted that, by 2055, exclusive economic zones (EEZ) average catch potentials in Nordic countries [such as Greenland (Denmark), Iceland, and Norway] would increase by 18–45 % and in the Alaskan (USA) and Russian Pacific EEZ by around 20 %. In most EEZs around the world, catch potentials would decline by various degrees, with Indonesia having the largest projected decline: over 20 % across the 45 species currently targeted within its EEZ (Cheung et al. 2009).

Rising sea levels will have an impact on freshwater fisheries and aquaculture. On the other hand, higher sea levels may also create new environments and opportunities for the fisheries and aquaculture sector (e.g., for coastal aquaculture and mangrove development). Increased frequency and intensity of storms could directly endanger infrastructure used for fisheries and aquaculture. Inland, the impacts on freshwater fisheries and aquaculture are also expected to be significant with increased variability in rainfall patterns as well as air and water temperatures affecting the productivity of rivers, lakes, and flood plains. For aquaculture, broader changes in hydrological conditions and seasonal changes in temperature, pH, salinity, and ecosystem health are all expected to change productivity and increase risks. To address these changes, some production systems may need to be relocated. Impacts on postharvest activities, on value addition, and on the distribution of fish to local, national, and global markets may also be significant, with potential changes in location and variability of supplies and changes in access to other key inputs, such as energy and water for processing.

4.9 Pests, Diseases, and Weeds

Climate affects not just agricultural crops but their associated pests (weeds, insects, and pathogens) as well. The distribution and proliferation of weeds, fungi, and insects are determined to a large extent by climate. Organisms become pests when they compete with, or prey upon, crop plants or cause disease in crop plants to an extent that reduces productivity. Not only does climate affect the type of crops grown and the intensity of the pest problems, it affects the pesticides often used to control or prevent outbreaks. The intensity of rainfall and its timing with respect to pesticide application are important factors in pesticide effectiveness, persistence, and transport.

As temperature increases, the pests will become more abundant through a number of interrelated processes, including range extensions and phenological changes, as well as increased rates of population development, growth, migration, and overwintering. The climate change is likely to alter the balance between pests, their natural enemies, and their hosts. The rise in temperature will favor pest development and winter survival. Rising atmospheric carbon dioxide concentrations may lead to a decline in food quality for plant-feeding insects, as a result of reduced foliar nitrogen levels. The epidemiology of plant diseases will be altered. The prediction of disease outbreaks will be more difficult in periods of rapidly changing climate and unstable weather. Environmental instability and increased incidence of extreme weather may reduce the effectiveness of pesticides on targeted pests or result in more injury to nontarget organisms.

Indications suggest that pests, such as aphids (Newman 2004) and weevil larvae, respond positively to elevated CO_2. Increased temperatures also reduced the overwintering mortality of aphids, enabling earlier and potentially more widespread dispersion. Evidence suggests that in sub-Saharan Africa migration patterns of locusts may be influenced by rainfall patterns, and thus potential exists for climate change to shape the impacts of this devastating pest. Pathogens and diseases may also be affected by a changing climate. This may be through impacts of warming or drought on the resistance of crops to specific diseases and through the increased pathogenicity of organisms by mutation induced by environmental stress (Gregory et al. 2009). Over the next 10–20 years, disease affecting oilseed rape could increase in severity within its existing range as well as spread to more northern regions where at present it is not observed.

Because climate variables (especially temperature, wind, and humidity) control the geographic distribution of pests, climate change is likely to alter their ranges. Insects may extend their ranges where warmer winter temperatures allow their overwintering survival and increase the possible number of generations per season (Stinner et al. 1989). Pests and diseases from low-latitude regions, where they are much more prevalent, may be introduced at higher latitudes. As a consequence of pest increase, there may be a substantial rise in the use of agricultural chemicals in both temperate and tropical regions to control them.

4.10 UV-B Radiation

One class of atmospheric trace gases, the chlorofluorocarbons (CFCs), has an important additional effect on the atmosphere; their photodegradation products act to destroy ozone (O_3) in the stratosphere. Ozone is a strong absorber of solar ultraviolet radiation, and the stratospheric ozone layer acts to filter out much of the ultraviolet component of the solar spectrum before it penetrates to the earth's surface. Thus, depletion of stratospheric O_3 allows more solar UV to reach the earth's surface.

Under clear-sky conditions, the ambient UV-B flux in tropical rice-growing areas is already among the highest on the earth's surface because the stratospheric ozone layer is naturally thinner than at high latitudes and because solar angles are higher. Thus, with stratospheric ozone depletion, the UV-B flux in tropical areas is likely to exceed that experienced anywhere in the world.

Clouds can reduce UV-B transmission through the atmosphere. Thus, in the tropics where there is a strong monsoon-driven seasonality in cloud cover, actual UV-B radiation during certain times of the year may be lower than predicted for clear skies. However, the quantitative effects of clouds on UV-B have not been clearly determined.

The IPCC assumes a further increase of surface ozone (O_3) until the end of the century (Vinzargan 2004) which may lead to considerable crop losses at least until 2030, especially in China (Van Deningen et al. 2009).

The release of chlorofluorocarbons has severely depleted the atmosphere's protective ozone layer. In general, each 1 % reduction in the ozone layer causes a 2 % increase in the amount of ultraviolet radiation that reaches the earth. In a recent study, two-thirds of the 300 species and cultivars examined appeared susceptible to ultraviolet radiation damage. This study suggests that 25 % depletion in the ozone layer could reduce soybean yields by 20 % (Pitovranov et al. 1988).

Unlike soybeans, some crops may be more tolerant of ultraviolet radiation. However, such crops also may be more susceptible to disease. For example, although wheat seems to tolerate ultraviolet radiation, "Red Hard" infection rates increased from 9 to 20 % when experimental ultraviolet radiation was increased from 8 to 16 % above ambient levels (Kettunen et al. 1988). Disease rates in rice also have increased when rice is exposed to higher ultraviolet radiation than normal (Bergthorsson et al. 1988).

4.10.1 UV-B Effects

Effects of UV-B on terrestrial biota, both direct and indirect, have been demonstrated at every level of biological organization, from plant molecules to entire ecosystems. Among the observed effects are:

- A number of plant molecules, such as DNA, lipids, and proteins strongly absorb UV-B and can, in turn, induce specific changes in tissue and whole-plant structure and function (Caldwell et al. 1989).
- UV-B can reduce plant growth and yield through reductions in biomass production, seed yield, and yield quality (Barnes et al. 1988).
- UV-B can alter plant morphology through reductions in plant height and leaf area, increased tillering, and changes in plant geometry (Barnes et al. 1988).
- Plant physiological processes are impacted by UV-B. Photosynthesis is often reduced, and the production of plant secondary metabolites increased (Caldwell et al. 1989).
- Plant competitive interactions can shift due to the differential sensitivity of competing plant species (Fox and Caldwell 1978; Barnes et al. 1988).
- Pest–pathogen relationships may be altered due to changes in plant secondary metabolites (Caldwell et al. 1989).

4.10.2 Ozone

Ozone is a major secondary air pollutant, which at current concentrations has been shown to have significant negative impacts on crop yields (Fig. 4.10) (Van Dingenen et al. 2009). Whereas in North America and Europe, emissions of ozone precursors are decreasing, in other regions of the world, especially Asia, they are increasing rapidly (Van Dingenen et al. 2009).

Ozone reduces agricultural yield through several mechanisms. Firstly, acute and visible injury to products such as horticultural crops reduces market value. Secondly, ozone reduces photosynthetic rates and accelerates leaf senescence which in turn impacts on final yield. In Europe and North America, many studies have investigated such yield reductions.

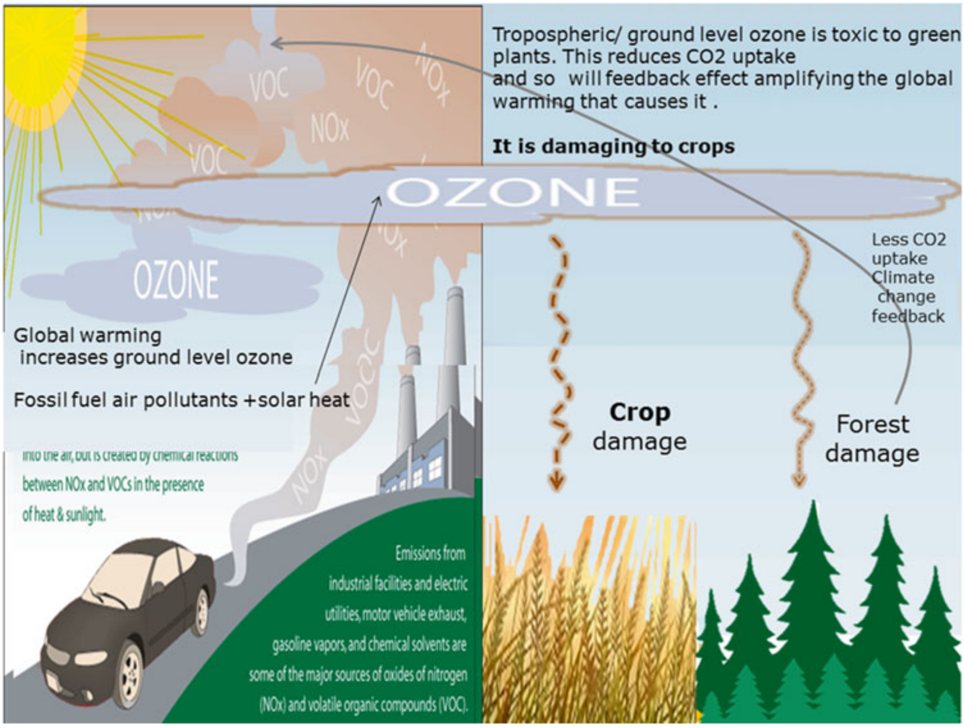

Fig. 4.10 Effect of ozone on crop damage

4.11 Crop Yields and Quality

4.11.1 Crop Yields

In the time span of 1981–2001, changes in precipitation and increased temperatures have already resulted in annual combined losses of wheat, maize, and barley of roughly 40 million tons per year. While the scientists consider these losses relatively small in comparison to the technological yield gains over the same period, the results demonstrate the negative impacts of climate change already occurring on crop yields at a global scale.

Parry et al. (2004) who are strongly involved in the IPCC computed future yields for wheat, rice, maize, and soybean under different emissions and socioeconomic scenarios until 2080. The results show that, in general, crop yields decrease in developing countries and yields increase in developed countries. On a global scale, the production of the four crops would be sufficient to feed the world under all scenarios. However, this is only possible if food distribution from the industrialized countries in the North to the less developed countries in the South takes place.

Individual crops vary in their response to climate change, however, making generalizations difficult. A crop-by-crop and region-by-region analysis is needed. However, moisture is vital in all crop production, and less moisture is certain to be a major limiting factor in North America. Also, heat stress may be a problem for crops such as corn and potatoes.

In eastern and Central Africa especially, the picture is different due to projected higher rainfall. Increased yields of 10–30 % are possible if rainfall increases and improved agricultural technologies are adopted (Messenger 1988). Even these projected increases, however, will not be sufficient to provide adequate food for Africa's growing population (Pedgley 1989). Providing adequate food supplies in several African countries will be most difficult because of the self-serving economic policies and ineffective food aid and poverty programs (Beresford and Fullerton 1989).

In Africa, the projected rise in rainfall associated with global warming is encouraging, especially since Africa already suffers from severe rainfall shortages. Therefore, the 10 % increase in rainfall will help improve crop yields, but it will not solve Africa's food problems. Water shortages will persist, and serious crop losses from pests are expected to continue.

Changes in temperature, moisture, carbon dioxide, insect pests, plant diseases, and weeds associated with global warming are projected to reduce food production in North America. The extent of alterations in crop yields will depend on each crop and its particular environmental requirements. However, improved agricultural technologies could partially offset decreased yields.

Additional research is needed on the potential impacts of climate change, including research on the temperature-induced degradation of soil, water, and biological resources and their potential impact on crop production.

Farmers in North America and Africa also need to adopt sound ecological resource management practices, especially soil and water conservation. These practices would benefit agriculture, the environment, farmers, and society, enabling agriculture to remain productive and offsetting some of the negative impacts of global warming.

Smaller farms are dependent on timely and sufficient rainfall during the monsoon for high crop yields. However, with the changing climate, rainfall patterns have become erratic and reduced, leaving farmers exposed to many risks including droughts, floods, diseases of both crops and animals, and unpredictable market irregularities (Venkateswarlu 2009). Indeed it is estimated that every 1 °C increase in temperature is likely to lead to a 5–10 % reduction in yields of some crops (Pachauri 2009).

Increased temperatures have drastically affected the rice production due to decrease crop duration in the Philippines (10 % reduction in yield in rice per 1 °C rise in temperature) (Peng et al. 2004). An increase of 6 °C in temperature and precipitation deficit of 300 mm reduced the maize yield by 36 % in the European Union (Ciais et al. 2005).

Numerous studies have examined the impacts of past climatic variations on agriculture. Such studies have clearly demonstrated the sensitivity of both temperate and tropical agricultural systems and nations to climatic variations and changes. In the temperate regions, the impacts of climate variability, particularly drought, on yields of grains in North America and the Soviet Union have been of particular concern because of their effects on world food security. In the tropics, drought impacts on agriculture and resulting food shortages have been widely studied, especially when associated with the failure of the monsoon in Asia or the rains in Sudano-Sahelian Africa. In the temperate regions, climatic variations are associated with economic disruptions; in the tropics, droughts bring famine and widespread social unrest (Pierce 1990).

At lower latitudes, especially in seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increases (1–2 °C), which would increase the risk of hunger (IPCC 2007). Fischer et al. (1996) projected the most significant negative changes for developing countries in Asia, where agricultural production declines of about −4 % to −10 % are anticipated under different socioeconomic and climate change scenarios.

4.11.2 Quality

According to the IPCC's TAR, "The importance of climate change impacts on grain and forage quality emerges from new research. For rice, the amylose content of the grain, a major determinant of cooking quality, is increased under elevated CO_2". Cooked rice grain from plants grown in high-CO_2 environments would be firmer than that from today's plants. However, concentrations of iron and zinc, which are important for human nutrition, would be lower. Moreover, the protein content of the grain decreases under combined increases of temperature and CO_2 (Woodward and Kelly 1995). Studies using

FACE have shown that increases in CO_2 lead to decreased concentrations of micronutrients in crop plants (Bert et al. 1997). This may have knock-on effects on other parts of ecosystems as herbivores will need to eat more food to gain the same amount of protein (Royal Society 2005).

Studies have shown that higher CO_2 levels lead to reduced plant uptake of nitrogen (and a smaller number showing the same for trace elements such as zinc), resulting in crops with lower nutritional value (IPCC 2001; Loladze 2002). This would primarily impact on populations in poorer countries less able to compensate by eating more food, more varied diets, or possibly taking supplements.

Reduced nitrogen content in grazing plants has also been shown to reduce animal productivity in sheep, which depend on microbes in their gut to digest plants, which in turn depend on nitrogen intake (IPCC 2001).

Most plants obtain carbon, their major constituent, via photosynthesis from atmospheric CO_2, and more CO_2 usually benefits plant growth. Before industrialization, around the year 1750, levels of CO_2 in the air were at 280 ppm; in 2005 it reached 380 ppm, and a level of 560 ppm can be expected by the end of the twenty-first century (IPCC 2007).

Computer models, which calculate future yields under climate change, usually incorporate increasing atmospheric CO_2 as the "fertilization effect." Experiments with elevated CO_2 indeed show increased biomass production and crop yields for most plants. However, higher yields in tons per hectare might be useless, when the nutritional value of the harvest is much lower.

Cotrufo et al. (1998) evaluated 75 studies on nitrogen/protein content under elevated CO_2 and found that nitrogen concentrations were reduced by an average of 9 % (for belowground tissues) to a 14 % (for aboveground tissues). While Cotrufo et al. (1998) evaluated studies on all kinds of plants, Loladze (2002) looked more specifically at food crops. His results show an average nitrogen reduction of 15–20 % as well as substantial reductions of other important micronutrients such as zinc and iron. A meta-analysis of 228 experimental observations (elevated CO_2 compared to ambient CO_2) of barley, rice, wheat, soybean, and potato showed a reduction of grain protein concentration of 10–15 % in wheat, barley, and rice. The reduction in potato tuber protein concentration was 14 %. For soybean, there was a much smaller reduction of protein concentration of 1.4 %. There is a general trend of nitrogen reduction (6 %) for rice, but no significant reduction of zinc and iron.

In response to Loladze (2002), other researchers investigated the experimental settings of enriched CO_2 experiments and analyzed rice grain samples from an open-field experiment. Quite opposite to Loladze (2002), the analysis showed increased micronutrient content in rice grains from the field with elevated CO_2. They argue that the reduction of micronutrients observed in other experiments is likely due to reduced nutrient availability in experimental soils and/or in limited root growth in pots.

The analysis of numerous studies on the grain quality of wheat under elevated CO_2 confirmed the lower protein levels and suggests that protein concentrations in wheat grains may decrease to values below the minimum quality standard for bread-making. Significantly lower concentrations of amino acids, zinc, iron, and other nutrients were also detected, but these reductions were observed only in chamber experiments, which were criticized.

However, while it is not clear if higher CO_2 levels decrease the content of micronutrients, it seems very clear that the protein content is significantly reduced in most crop plants. Therefore, results of computer models which calculate yields in metric tons must be interpreted with caution, with regard to food security. It would be much more useful to have results in energy units (Calorie or Joule) instead of tons/ha.

4.12 Sea-Level Rise

Sea-level rise is an inevitable consequence of a warming climate owing to a combination of thermal expansion of the existing mass of ocean water and addition of inundation of coastal land, especially where the capacity for introduction or modification of sea defenses is relatively low or nonexistent. Regarding crop productivity, vulnerability is clearly greatest where large sea-level rise occurs in conjunction with low-lying coastal agriculture. Many major river deltas provide important agricultural land owing to the fertility of alluvial soils, and many small island states are also low lying. Increases in mean sea level threaten to inundate agricultural lands and salinize groundwater in the coming decades to centuries, although the largest impacts may not be seen for many centuries owing to the time required to melt large ice sheets and for warming to penetrate into the deep ocean.

The potential sea-level rise associated with melting of the main ice sheets would be 5 m for West Antarctic Ice Sheet (WAIS), 60 m for East Antarctic Ice Sheet (EAIS), and 7 m for Greenland Ice Sheet (GIS), with both the GIS and WAIS considered vulnerable. Due to the possible rate of discharge of these ice sheets, and past maximal sea-level rise (under similar climatic conditions), a maximum eustatic sea-level rise of approximately 2 m by 2100 is considered physically plausible, but very unlikely.

Water expands when heated and sea levels are expected to rise due to climate change. Rising sea levels will also result as the polar caps begin to melt. Rising sea levels is already affecting many small islands. The World Watch Institute reports that "the Earth's ice cover is melting in more places and at higher rates than at any time since record keeping began" (March 6, 2000). Rising sea levels will impact many coastlines, and a large mass of humanity lives near the coasts or by major rivers. Analysis by the World Wildlife Fund has found that many cities are unprepared for climate change effects such as rising sea levels.

CO_2-induced warming is expected to lead to rises in sea level as a result of thermal expansion of the oceans and partial melting of glaciers and ice caps, and this in turn is expected to affect agriculture, mainly through the inundation of low-lying farmland but also through the increased salinity of coastal groundwater. The IPCC estimate of sea-level rise above present levels under the business-as-usual scenario is 9–29 cm by the year 2030 with a best estimate of 18 cm and 28–96 cm by 2090 with a best estimate of 58 cm (Pearch and Bjorkman 1983).

Preliminary surveys of proneness to inundation have been based on a study of existing contoured topographic maps, in conjunction with knowledge of the local "wave climate" that varies between different coastlines. They have identified 27 countries as being especially vulnerable to sea-level rise, on the basis of the extent of land liable for inundation, the population at risk, and the capability of taking protective measures (UNEP 1989). It should be emphasized, however, that these surveys assume a much larger rise in sea levels (1.5 m) than is at present estimated to occur within the next century under current trends of increase of GHG concentrations. On an ascending scale of vulnerability (1–10), experts identified the following most vulnerable countries or regions: 10, Bangladesh; 9, Egypt and Thailand; 8, China; 7, western Denmark; 6, Louisiana; and 4, Indonesia.

The most severe effects on agriculture are likely to stem directly from inundation. Southeast Asia would be most affected because of the extreme vulnerability of several large and heavily populated deltaic regions. For example, with a 1.5 m sea-level rise, about 15 % of all land (and about one-fifth of all farmland) in Bangladesh would be inundated, and a further 6 % would become more prone to frequent flooding (UNEP 1989). Altogether 21 % of agricultural production could be lost.

In South, Southeast, and East Asia, about 10 % of the regional rice production, which is enough to feed 200 million people, is from the areas that are susceptible to 1 m rise in the sea level. Direct loss of land combined with less favorable hydraulic conditions may reduce rice yields by 4 % if no adaptation measures are taken, endangering the food security of at least 75 million people. Saltwater intrusion and soil salinization are other concerns for agricultural productivity.

In Egypt, it is estimated that 17 % of national agricultural production and 20 % of all farmland, especially the most productive farmland, would be lost as a result of a 1.5 m sea-level rise.

Island nations, particularly low-lying coral atolls, have the most to lose. The Maldives Islands in the Indian Ocean would have one-half of their land area inundated with a 2 m rise in sea level (UNEP 1989).

In addition to direct farmland loss from inundation, it is likely that agriculture would experience increased costs from saltwater intrusion into surface water and groundwater in coastal regions. Deeper tidal penetration would increase the risk of flooding, and rates of abstraction of groundwater might need to be reduced to prevent recharge of aquifers with sea water.

Further indirect impacts would be likely as a result of the need to relocate both farming populations and production in other regions. In Bangladesh, for example, about one-fifth of the nation's population would be displaced as a result of the farmland loss estimated for a 1.5 m sea-level rise. It is important to emphasize, however, that the IPCC estimates of sea-level rise are much lower than this (about 0.5 m by 2090 under the business-as-usual scenario).

The rise in sea levels and tropical cyclones are major threats to rice production in the Asian mega deltas especially in Vietnam, Bangladesh, and Myanmar.

4.13 Increasing Ocean Acidification

Although it has gained less mainstream media attention, the effects of increasing greenhouse emissions – in particular carbon dioxide – on the oceans may well be significant. The oceans are taking up atmospheric CO_2, but this uptake results in chemical reactions which make the oceans more acidic. Oceanic acidification may disrupt important marine ecosystems by interfering with the ability of marine organisms to develop carbonate and by dissolving carbonate sediments.

As explained by the US agency, the National Oceanic and Atmospheric Administration (NOAA) (Fig. 4.11), the basic chemistry of ocean acidification is well understood.

These are the three main concepts:

- More CO_2 in the atmosphere means more CO_2 in the ocean.
- Atmospheric CO_2 is dissolved in the ocean, which becomes more acidic.
- The resulting changes in the chemistry of the oceans disrupt the ability of plants and animals in the sea to make shells and skeletons of calcium carbonate, while dissolving shells already formed.

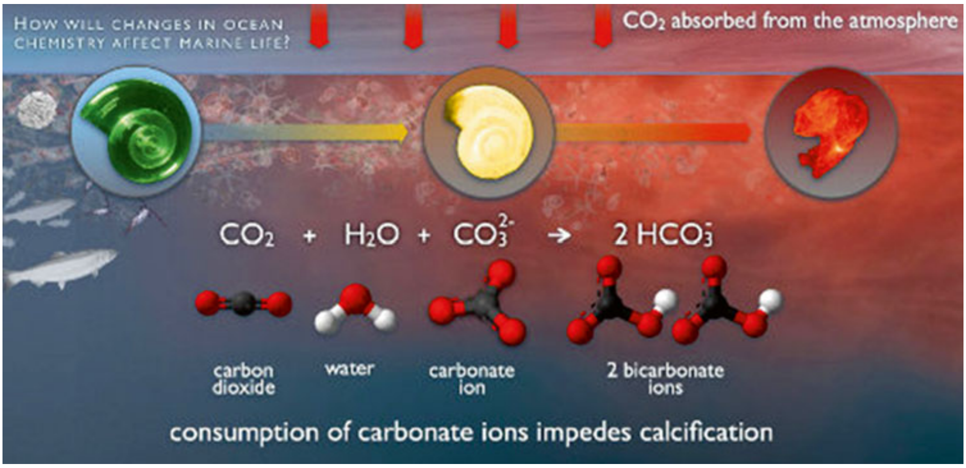

Fig. 4.11 Ocean acidification; consumption of carbonate ions impede calcification (Source: Pacific Marine Environment Laboratory, NOAA)

Scientists have found that oceans are able to absorb some of the excess CO_2 released by human activity. This has helped keep the planet cooler than it otherwise could have been had these gases remained in the atmosphere.

However, the additional excess CO_2 being absorbed is also resulting in the acidification of the oceans: When CO_2 reacts with water, it produces a weak acid called carbonic acid, changing the sea water chemistry. As the Global Biodiversity Outlook report explains, the water is some 30 % more acidic than preindustrial times, depleting carbonate ions – the building blocks for many marine organisms.

In addition, "concentrations of carbonate ions are now lower than at any time during the last 800,000 years. The impacts on ocean biological diversity and ecosystem functioning will likely to be severe, though the precise timing and distribution of these impacts are uncertain."

Although millions of years ago CO_2 levels were higher, today's change is occurring rapidly, giving many marine organisms too little time to adapt. Some marine creatures are growing thinner shells or skeletons, for example. Some of these creatures play a crucial role in the food chain and in ecosystem biodiversity.

Some species may benefit from the extra carbon dioxide, and a few years ago, scientists and organizations, such as the European Project on Ocean Acidification, formed to try to understand and assess the impacts further.

One example of recent findings is that a tiny sand grain-sized plankton responsible for the sequestration of 25–50 % of the carbon the oceans absorb is affected by increasing ocean acidification. This tiny plankton plays a major role in keeping atmospheric CO_2 concentrations at much lower levels than they would be otherwise so large effects on them could be quite serious.

Other related problems reported by the Inter Press Service include more oceanic dead zones (areas where there is too little oxygen in the sea to support life) and the decline of important coastal plants and forests, such as mangrove forests that play an important role in carbon absorption. This is on top of the already declining ocean biodiversity that has been happening for a few decades now.

Scientists now believe that ocean acidification is unparalleled in the last 300 million years, "raising the possibility that we are entering an unknown territory of marine ecosystem change."

4.14 Glacier Retreat and Disappearance

The continued retreat of glaciers will have a number of different quantitative impacts. In areas that are heavily dependent on water runoff from glaciers that melt during the warmer summer months, a continuation of the current retreat will eventually deplete the glacial ice and substantially reduce or eliminate runoff (Fig. 4.12). A reduction

Fig. 4.12 *Left*: Milk Lake Glacier in 1988 clinging to the slope above the greenish lake. *Right*: Milk Lake in 2009, the glacier now entirely gone

in runoff will affect the ability to irrigate crops and will reduce summer stream flows necessary to keep dams and reservoirs replenished.

Approximately 2.4 billion people live in the drainage basin of the Himalayan Rivers. The River Ganges could provide water for drinking and farming for more than 500 million people in India, China, Pakistan, Afghanistan, Bangladesh, Nepal, and Myanmar. The west coast of North America, which gets much of its water from glaciers in mountain ranges such as the Rocky Mountains and Sierra Nevada, also would be affected.

Satellite observations show the Arctic sea ice is decreasing, and projections for the rest of the century predict even more shrinkage.

4.14.1 Changes in Water Availability

In some rivers such as the Nile, climate change increases flow throughout the year which could confer benefits to agriculture. However, in other catchments, e.g., the Ganges, the increase in runoff comes as an increase in peak flow around the monsoon. However, dry season river flow is still very low. Without sufficient storage of peak season flow, water scarcity may affect agricultural productivity despite overall increases in annual water availability. Increases at peak flow may also cause damage to crop lands through flooding.

Although additional river flow can be considered beneficial to agriculture, this is only true if there is an ability to store runoff during times of excess to use later in the growing season. Globally, only a few rivers currently have adequate storage to cope with large shifts in seasonality of runoff. Where storage capacities are not sufficient, much of the winter runoff will immediately be lost to the oceans.

The majority of observed glaciers around the globe are undergoing shrinkage. There is a broad consensus that warming is a primary cause of retreat, although changes in atmospheric moisture particularly in the tropics may be contributing (Bates et al. 2008). Melting glaciers will initially increase river flow, although the seasonality of flow will be enhanced bringing with it an increased flood risk. In the long term, glacial retreat is expected to be enhanced further leading to eventual decline in runoff, although the greater time scale of this decline is uncertain.

Analysis of glaciers in the western Himalayas demonstrates evidence of glacial thinning. The limited number of direct observations also supports evidence of a glacial retreat in the Himalayas.

4.15 ENSO Effects on Agriculture

ENSO (El Niño Southern Oscillation) will affect monsoon patterns more intensely in the future as climate change warms up the ocean's water. Crops that lie on the equatorial belt or under the tropical Walker circulation, such as rice, will be affected by varying monsoon patterns and more unpredictable weather. Scheduled planting and harvesting based on weather patterns will become less effective.

Areas such as Indonesia where the main crop consists of rice will be more vulnerable to the increased intensity of ENSO effects in the future of climate change. University of Washington professor David Battisti researched the effects of future ENSO patterns on the Indonesian rice agriculture using IPCC's 2007 annual report (UN Environment Program 2008) and 20 different logistical models mapping out climate factors such as wind pressure, sea level, and humidity and found that rice harvest will experience a decrease in yield. Bali and Java, which holds 55 % of the rice yields in Indonesia, will be likely to experience 9–10 % probably of delayed monsoon patterns, which prolongs the hungry season. Normal planting of rice crops begins in October and harvest by January. However, as climate change affects ENSO and consequently delays planting, harvesting will be late and in drier conditions, resulting in less potential yields (Brown 2005).

4.16 Climate Change Impacts on Food Security

FAO defines food security in four dimensions, namely, food availability, access to food, stability of food supply, and utilization of food. This goes far beyond food production. In the short term, socioeconomic factors such as those linked with market forces may dominate food security. However, in terms of the long-term stability and sustainability of food production and food supply, environmental factors become crucial. Although there will be some positive impacts, the following list illustrates that climate change will have mostly negative effects on the food security dimensions:

- Availability of food – will be a drop in food production caused by extreme events, changes in the suitability or availability of arable land and water, and the unavailability or lack of access to crops, crop varieties, and animal breeds that can be productive in conditions which have lead to changes in pests and diseases
- Access to food – will be worsened by climate change events that lead to damages in infrastructure and losses of livelihood assets as well as loss of income and employment opportunities
- Stability of food supply – could be influenced by food price fluctuations and a higher dependency on imports and food aid
- Utilization of food – can be affected indirectly by food safety hazards associated with pests and animal diseases as well as the increased presence of human diseases such as malaria and diarrhea.

Although climate change impacts on food security on national and subnational levels remain highly uncertain, the following IPCC regional assessments project regional variations in climate change impact.

4.16.1 Food Insecurity Hotspots

Food insecurity vulnerability patterns will be modified by climate change. Small-scale rainfed farming systems, pastoralist systems, inland and coastal fishing and aquaculture communities, and forest-based systems are particularly vulnerable to climate change. Moreover, the urban poor, particularly in coastal cities and flood plain settlements, face increasing risks. Generally, impacts of climate change on smallholder and subsistence farmers, pastoralists, artisanal fisherfolk, and forest dwellers including indigenous people are complex and highly localized. Vulnerability also varies within communities, dependent on factors such as land ownership, gender, age, and health.

Globally, the IPCC expects only a marginal increase in the number of people facing hunger due to climate change. However, many of the 82 low-income food-deficit countries have only limited financial capacity and rely heavily on their own production. It may not be possible to offset declines in local supply without increased reliance on food aid.

Global studies must include comprehensive national assessments of climate change impacts on agriculture and food security to support national and subnational decision making. While existing studies mainly focus on the effect of downscaled climate change scenarios on major crops, future studies should look at a wider range of crops and also take into account food delivery systems, the greater international connectivity, food prices, agricultural policy implications, and possible development pathways. However, in some regions, such as large parts of Africa, studies are hampered by highly uncertain trends in rainfall, the insufficient resolution of climate models, and lack of climate observation data.

In additions, studies should also consider the increasing competition over land use because of the demand for agrofuel; the impact of climate change and CO_2 fertilization on pests, weeds, and diseases; and the role of land tenure and rights systems in accessing natural resources.

4.17 Conclusions

In general, the tropical regions appear to be more vulnerable to climate change than the temperate regions for several reasons. On the biophysical side, temperate C3 crops are likely to be more responsive to increasing levels of CO_2. Second, tropical crops are closer to their high temperature optima and experience high temperature stress, despite lower projected amounts of warming. Third, insects and diseases already much more prevalent in warmer and more humid regions may become even more widespread.

Tropical regions may also be more vulnerable to climate change because of economic and social constraints. Greater economic and individual dependence on agriculture, widespread poverty, inadequate technologies, and lack of political power are likely to exacerbate the impacts of climate change in tropical regions.

In the light of possible global warming, plant breeders should probably place even more emphasis on the development of heat- and drought-resistant crops. Research is needed to define the current limits to these resistances and the feasibility of manipulation through modern genetic techniques. Both crop architecture and physiology may be genetically altered to adapt to warmer environmental conditions. In some regions, it may be appropriate to take a second look at traditional technologies and crops as ways of coping with climate change.

At the regional level, those charged with planning for resource allocation, including land, water, and agriculture development, should take climate change into account. In coastal areas, agricultural land may be flooded or salinized; in continental interiors and other locations, droughts may increase. These eventualities can be dealt with more easily if anticipated.

As climatic factors change, a host of consequences will ripple through the agricultural system, as human decisions involving farm management, grain storage facilities, transportation infrastructure, regional markets, and trade patterns respond. For example, field-level changes in thermal regimes, water conditions, pest infestations, and, most importantly, quantity and quality of yields may lead to changes in farm management decisions based on altered risk assessments. Consequences of these management decisions could result in local and regional alterations in farming systems, land use, and food availability. Ultimately, impacts of climate change on agriculture may reverberate throughout the international food economy and global society.

At the national and international levels, the needs of regions and people vulnerable to the effects of climate change on their food supply should be addressed. In many cases, reducing vulnerability to current climate variability should also serve to mitigate the impacts of global warming.

It is important to ask, “What will or should agriculture be like in the next century?” Even if the answer is unknown, the flexibility gained in attempting to imagine the agricultural future should be a useful tool for adaptation to climate change.

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Regional Impacts

5

Abstract

Regional effects of global warming are long-term significant changes in the expected patterns of average weather of a specific region due to global warming. The world average temperature is rising due to the greenhouse effect caused by increasing levels of greenhouse gases, especially carbon dioxide. The changes in climate are not expected to be uniform across the earth, when the global temperature changes. In particular, land areas change more quickly than oceans, and northern high latitudes change more quickly than the tropics, and the margins of biome regions change faster than do their cores.

Regional effects of global warming vary in nature. Some are the result of a generalized global change, such as rising temperature, resulting in local effects, such as melting ice. In other cases, a change may be related to a change in a particular ocean current or weather system. In such cases, the regional effect may be disproportionate and will not necessarily follow the global trend.

There are three major ways in which global warming will make changes to regional climate: melting or forming ice, changing the hydrological cycle (of evaporation and precipitation), and changing currents in the oceans and air flows in the atmosphere. The coast can also be considered a region and will suffer severe impacts from sea-level rise.

Keywords

Regional impacts • Global warming • Greenhouse gases • Adaptation • Vulnerability • Sustainability

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5.1 Africa

- Food insecurity worsening and number of people at risk from hunger increasing.
- Agricultural production severely compromised due to loss of land, shorter growing seasons, and more uncertainty about what and when to plant. By 2020, yields from rainfed crops could be halved in some countries, and by 2100, net revenues from crops could fall by 90 %.
- General decline in most subsistence crops such as sorghum in Sudan, Ethiopia, Eritrea, and Zambia; maize in Ghana; millet in Sudan; and groundnuts in Gambia.
- Fish stocks already compromised will be depleted further by rising water temperatures and other physical and ecosystem changes. Threats of inundation for coast of East Africa; coastal deltas, such as the Nile; and degradation of marine ecosystems and other physical and ecosystem changes.
- Grassland degradation, with widespread drying and desertification, particularly in the Sahel and southern Africa.
- Forests face deforestation, degradation, and increase in forest fires.

In Africa, the IPCC (2007) projected that climate variability and change would severely compromise agricultural production and access to food. This projection was assigned "high confidence."

Africa's geography makes it particularly vulnerable to climate change, and 70 % of the population relies on rainfed agriculture for their livelihoods. Tanzania's official report on climate change suggests that the areas that usually get two rainfalls in the year will probably get more and those that get only one rainy season will get far less. The net result is expected to be that 33 % less maize – the country's staple crop – will be grown (FAO Newsroom 2006).

Water is one of several current and future critical issues facing Africa. Water supplies from rivers, lakes, and rainfall are characterized by their unequal natural geographical distribution and accessibility and unsustainable water use. Climate change has the potential to impose additional pressures on water availability and accessibility. Arnell et al. (2004) described the implications of the IPCC's SRES scenarios for a river runoff projection for 2050 using the HadCM320 climate model. These experiments indicate a significant decrease in runoff in the north and south of Africa, while the runoff in East Africa and parts of semiarid sub-Saharan Africa is projected to increase. However, multi-model results show considerable variation among models, with the decrease in northern Africa and the increase in East Africa emerging as the most robust responses. There is a widespread in projections of precipitation in sub-Saharan Africa, with some models projecting increases and others decreases. Projected impacts should be viewed in the context of this substantial uncertainty.

A specific example is the southwestern Cape, South Africa, where one study shows water supply capacity decreasing either as precipitation decreases or as potential evaporation increases. This projects a water supply reduction of 0.32 % per year by 2020, while climate change associated with global warming is projected to raise water demand by 0.6 % per year in the Cape Metropolitan Region. With regard to the Nile Basin, there is no clear indication of how Nile River flow would be affected by climate change, because of uncertainty in projected rainfall patterns in the basin and the influence of complex water management and water governance structures.

Responses to rainfall shifts are already being observed in many terrestrial water sources that could be considered possible indicators of future water stress linked to climate variability. In the eastern parts of the continent, interannual lake level fluctuations have been observed, with low values in 1993–1997 and higher levels (e.g., of Lakes Tanganyika, Victoria and Turkana) in 1997–1998, the latter being linked to an excess in rainfall in late 1997 coupled with large-scale perturbations in the Indian Ocean. Higher water temperatures have also been reported in lakes in response to warmer conditions.

Impacts of climate change on growing periods and on agricultural systems and possible livelihood implications have been examined. A recent study based on three scenarios indicates that crop net revenues would be likely to fall by as much as

90 % by 2100, with small-scale farms being the most affected. However, there is the possibility that adaptation could reduce these negative effects.

A case study of climate change, water availability, and agriculture in Egypt is provided. Not all changes in climate and climate variability would, however, be negative for agriculture. The growing seasons in certain areas, such as around the Ethiopian highlands, may lengthen under climate change. A combination of increased temperatures and rainfall changes may lead to the extension of the growing season, for example, in some of the highland areas. As a result of a reduction in frost in the highland zones of Mt. Kenya and Mt. Kilimanjaro, for example, it may be possible to grow more temperate crops, e.g., apples, pears, barley, wheat, etc. (Parry et al. 2004).

Fisheries are another important source of revenue, employment, and protein. In coastal regions that have major lagoons or lake systems, changes in freshwater flows, and more intrusion of salt waters into the lagoons, would affect species that are the basis of inland fisheries or aquaculture.

The impact of climate change on livestock in Africa has been examined. Decreased precipitation of 14 % would be likely to reduce large farm livestock income by about 9 % (~US$5 billion) due to a reduction in both the stock numbers and the net revenue per animal owned.

5.1.1 Climate, Water Availability, and Agriculture in Egypt

Egypt is one of the African countries that could be vulnerable to water stress under climate change. The water used in 2000 was estimated at about 70 km^3 which is already far in excess of the available resources. A major challenge is to close the rapidly increasing gap between the limited water availability and the escalating demand for water from various economic sectors. The rate of water utilization has already reached its maximum for Egypt, and climate change will exacerbate this vulnerability.

Agriculture consumes about 85 % of the annual total water resources and plays a significant role in the Egyptian national economy, contributing about 20 % GDP. More than 70 % of the cultivated area depends on low-efficiency surface irrigation systems, which cause high water losses, a decline in land productivity, water logging, and salinity problems. Moreover, unsuitable agricultural practices and improper irrigation management affect the quality of the country's water resources. Reductions in irrigation water quality have, in their turn, harmful effects on irrigated soils and crops.

Institutional water bodies in Egypt are working to achieve the following targets by 2017 through the National Improvement Plan:

- Improving water sanitation coverage for urban and rural areas
- Wastewater management
- Optimizing the use of water resources by improving irrigation efficiency and agriculture drainage-water reuse

However, with climate change, an array of serious threats is apparent.

- Sea-level rise could impact on the Nile Delta and on people living in the delta and other coastal areas.
- Temperature rises will be likely to reduce the productivity of major crops and increase their water requirements, thereby directly decreasing crop water-use efficiency.
- There will probably be a general increase in irrigation demand.
- There will also be a high degree of uncertainty about the flow of the Nile.
- Based on SRES scenarios, Egypt will be likely to experience an increase in water stress, with a projected decline in precipitation and a projected population of between 115 and 179 million by 2050. This will increase water stress in all sectors.
- Ongoing expansion of irrigated areas will reduce the capacity of Egypt to cope with future fluctuations in flow.

5.1.2 Adaptation and Vulnerability

Recent studies in Africa highlight the vulnerability of local groups that depend primarily on natural resources for their livelihoods, indicating that their resource base – already severely stressed and degraded by overuse – is expected to be further impacted by climate change.

Climate change and variability have the potential to impose additional pressures on water availability, accessibility, supply, and demand in Africa. It is estimated that around 25 % (200 million) of Africa's population currently experiences water stress, with more countries expected to face high future risk. Moreover, it has been envisioned that, even without climate change, several countries, particularly in northern Africa, would reach the threshold level of their economically usable land-based water resources before 2025.

Frequent natural disasters, such as droughts and floods, have largely constrained agricultural development in Africa, which is heavily dependent on rainfall, leading to food insecurity in addition to a range of macro- and microstructural problems.

ENSO has a significant influence on rainfall at interannual scales in Africa and may influence future climate variability. However, a number of barriers hamper effective adaptation to variations in ENSO including spatial and temporal uncertainties associated with forecasts of regional climate, the low level of awareness among decision makers of the local and regional impacts of El Niño, limited national capacities in climate monitoring and forecasting, and lack of coordination in the formulation of responses.

Regarding the impacts of climate variability and change on groundwater, little information is available, despite many countries (especially in northern Africa) being dependent on such water sources.

Previous assessments of water impacts have not adequately covered the multiple future water uses and future water stress, and so more detailed research on hydrology, drainage, and climate change is required. Future access to water in rural areas, drawn from low-order surface water streams, also needs to be addressed by countries sharing river basins.

Adaptive capacity and adaptation related to water resources are considered very important to the African continent. Historically, migration in the face of drought and floods has been identified as one of the adaptation options. Migration has also been found to present a source of income for those migrants who are employed as seasonal labor. Other practices that contribute to adaptation include traditional and modern water-harvesting techniques, water conservation and storage, and planting of drought-resistant and early-maturing crops. The importance of building on traditional knowledge related to water harvesting and use has been highlighted as one of the most important adaptation requirements, indicating the need for its incorporation into climate change policies to ensure the development of effective adaptation strategies that are cost-effective, participatory, and sustainable.

Very little information exists regarding the cost of impacts and adaptation to climate change for water resources in Africa. However, an initial assessment in South Africa of adaptation costs in the Berg River Basin shows that the costs of not adapting to climate change can be much greater than those that may arise if flexible and efficient approaches are included in management options (Stern 2007).

5.2 Asia

- Crop yield decreases in many areas will put many millions of Asians at risk from hunger.
- Water stress will affect more than 100 million people due to decrease of freshwater availability in Central, South, East and Southeast Asia, particularly in large river basins such as Changjiang.
- Land degradation and desertification may increase due to reduced soil moisture and increased evapotranspiration. Grassland productivity is expected to decline by as much as 40–90 % with a temperature increase of 2–3 °C, combined with reduced precipitation in the semiarid and arid regions.
- Agriculture productivity may expand in northern areas.
- Boreal forest in north Asia may increase northward, although the likely increase in frequency and extent of forest fires could limit forest expansion.

- Fish breeding habitats, fish food supply, and, ultimately, the abundance of fish populations in Asian waters will be substantially altered. Aquaculture industry and infrastructure, particularly in heavily populated mega deltas, are likely to be seriously affected by coastal inundation.

Asia is a region where water distribution is uneven and large areas are under water stress. Among the 43 countries of Asia, 20 have renewable annual per capita water resources in excess of 3,000 m^3, 11 are between 1,000 and 3,000 m^3, and 6 are below 1,000 m^3 (there are no data from the remaining 6 countries). From west China and Mongolia to west Asia, there are large areas of arid and semiarid lands. Even in humid and subhumid areas of Asia, water scarcity/stress is one of the constraints for sustainable development. On the other hand, Asia has a very high population that is growing at a fast rate, low development levels, and weak coping capacity. Climate change is expected to exacerbate the water scarcity situation in Asia, together with multiple socioeconomic stresses.

Production of rice, maize, and wheat in the past few decades has declined in many parts of Asia due to increasing water stress, arising partly from increasing temperatures, increasing frequency of El Niño events, and reductions in the number of rainy days.

In East and Southeast Asia, the IPCC (2007) projected that crop yields could increase up to 20 % by the mid-twenty-first century. In Central and South Asia, projections suggested that yields might decrease by up to 30 %, over the same time period. These projections were assigned "medium confidence." Taken together, the risk of hunger was projected to remain very high in several developing countries.

More detailed analysis of rice yields by the International Rice Research Institute forecasts 20 % reduction in yields over the region per 1 °C of temperature rise. Rice becomes sterile if exposed to temperatures above 35 °C for more than 1 h during flowering and consequently produces no grain.

Agricultural irrigation demand in arid and semiarid regions of Asia is estimated to increase by at least 10 % for an increase in temperature of 1 °C. Rainfed crops in the plains of north and northeast China could face water-related challenges in future decades due to increases in water demand and soil-moisture deficit associated with projected declines in precipitation. However, that more than two-thirds of the models ensembled show an increase in precipitation and runoff for this region. In north China, irrigation from surface water and groundwater sources is projected to meet only 70 % of the water requirement for agricultural production, due to the effects of climate change and increasing demand. Enhanced variability in hydrological characteristics will be likely to continue to affect grain supplies and food security in many nations of Asia.

5.2.1 Adaptation and Vulnerability

There are different current water vulnerabilities in Asian countries. Some countries which are not currently facing high risk are expected to face a future risk of water stress, with various capacities for adaptation. Coastal areas, especially heavily populated mega delta regions in South, East, and Southeast Asia, are expected to be at greatest risk of increased river and coastal flooding. In southern and eastern Asia, the interaction of climate change impacts with rapid economic and population growth, and migration from rural to urban areas, is expected to affect development.

The vulnerability of a society is influenced by its development path, physical exposures, the distribution of resources, prior stresses, and social and government institutions. All societies have inherent abilities to deal with certain variations in climate, yet adaptive capacities are unevenly distributed, both across countries and within societies. The poor and marginalized have historically been most at risk and are most vulnerable to the impacts of climate change. Recent analyses in Asia show that marginalized, primary-resource-dependent livelihood groups are particularly vulnerable to climate change impacts if their natural resource base is severely stressed and degraded by overuse or if their governance systems are not capable of responding effectively.

There is growing evidence that adaptation is occurring in response to observed and anticipated climate change. For example, climate change forms part of the design consideration in infrastructure projects such as coastal defense in the Maldives and prevention of glacial lake outburst flooding in Nepal.

There are many adaptation measures that could be applied in various parts of Asia to minimize the impacts of climate change on water resources, several of which address the existing inefficiency in the use of water: modernization of existing irrigation schemes and demand management aimed at optimizing physical and economic efficiency in the use of water resources and recycled water in water-stressed countries; public investment policies that improve access to available water resources, encourage integrated water management and respect for the environment, and promote better practices for the sensible use of water in agriculture; and the use of water to meet non-potable water demands. After treatment, recycled water can also be used to create or enhance wetlands and riparian habitats.

Effective adaptation and adaptive capacity, particularly in developing Asian countries, will continue to be limited by various ecological, social and economic, technical, institutional, and political constraints. Water recycling is a sustainable approach towards adaptation to climate change and can be cost-effective in the long term. However, the treatment of wastewater for reuse that is now being practiced in Singapore, and the installation of distribution systems, can initially be expensive compared to water supply alternatives such as the use of imported water or groundwater.

5.3 Australia and New Zealand

- Water security problems to intensify by 2030 in southern and eastern Australia, New Zealand's Northland, and some eastern regions. Major land degradation problems such as erosion and salinization are likely to expand.
- Agricultural production is projected to decline by 2030 throughout much of southern and eastern Australia and throughout parts of eastern New Zealand, due to increased drought and fire. In contrast, there could be moderate yield increases in northeastern Australia and main parts of New Zealand due to a longer growing season, less frost, and increased rainfall.
- Livestock productivity in Australia is projected to suffer heat stress, lower pasture productivity, lower forage quality, and expansion of animal diseases such as cattle tick.
- Forests will benefit from CO_2 fertilization, higher rainfall, and longer growing season along with negative impacts of increased water stress, pests, fires, and erosion.
- Marine fisheries will have additional stress due to increasing sea surface temperature, rising sea level, acidification, and changes in the Southern Ocean circulation which will cause changes in species distribution, particularly for species at the edges of suitable habitats.

Although Australia and New Zealand are very different hydrologically and geologically, both are already experiencing water supply impacts from recent climate change, due to natural variability and to human activity. The strongest regional driver of natural climate variability is the El Niño Southern Oscillation cycle. Since 2002, virtually all of the eastern states and the southwest region of Australia have moved into drought. This drought is at least comparable to the so-called Federation droughts of 1895 and 1902 and has generated considerable debate about climate change and its impact on water resources and sustainable water management.

Large shifts in the geographical distribution of agriculture and its services are very likely. Farming of marginal land in drier regions is likely to become unsustainable due to water shortages, new biosecurity hazards, environmental degradation, and social disruption. Cropping and other agricultural industries reliant on irrigation are likely to be threatened where irrigation water availability is reduced. For maize in New Zealand, a reduction in growth duration reduces crop water requirements, providing closer synchronization of development with seasonal climatic conditions. The distribution of viticulture in both countries is likely to change depending upon suitability compared to high-yield pasture and silviculture and upon irrigation water availability and cost. Hennessy et al. (2007) assessed the literature for Australia and New Zealand and concluded that without further adaptation to climate change, projected impacts would likely to be substantial. By 2030, production from agriculture and forestry was projected to decline over much of southern and eastern Australia and over parts of eastern New Zealand. In New Zealand, initial benefits were projected close to major rivers and in western and southern areas. Hennessy et al. (2007) placed high confidence in these projections.

5.3.1 Adaptation and Vulnerability

Planned adaptation can greatly reduce vulnerability, and opportunities lie in the inclusion of risks due to climate change on the demand as well as the supply side. In major cities such as Perth, Brisbane, Sydney, Melbourne, Adelaide, Canberra, and Auckland, concerns about population pressures, ongoing drought in southern and eastern Australia, and the impact of climate change are leading water planners to consider a range of adaptation options. While some adaptation has already occurred in response to observed climate change (e.g., ongoing water restrictions, water recycling, seawater desalination), both countries have taken notable steps in building adaptive capacity by increasing support for research and knowledge, expanding assessments of the risks of climate change for decision makers, infusing climate change into policies and plans, promoting awareness, and dealing more effectively with climate issues. However, there remain environmental, economic, informational, social, attitudinal, and political barriers to the implementation of adaptation.

In urban catchments, storm and recycled water could be used to augment supply, although existing institutional arrangements and technical systems for water distribution constrain implementation. Moreover, there is community resistance to the use of recycled water for human consumption (e.g., in such cities as Toowoomba in Queensland and Goulburn in New South Wales). Installation of rainwater tanks is another adaptation response and is now actively pursued through incentive policies and rebates. For rural activities, more flexible arrangements for allocation are required, via the expansion of water markets, where trading can increase water-use efficiency. Substantial progress is being made in this regard. Under the National Water Initiative, states, territories, and the Australian Government are now committed to pursuing best-practice water pricing and institutional arrangements to achieve consistency in water charging.

When climate change impacts are combined with other non-climate trends, there are some serious implications for sustainability in both Australia and New Zealand. In some river catchments, where increasing urban and rural water demand has already exceeded sustainable levels of supply, ongoing and proposed adaptation strategies are likely to buy some time. Continued rates of coastal development are likely to require tighter planning and regulation if such developments are to remain sustainable.

5.4 Europe

- Crop productivity will have small increases overall that might be far outweighed by technological development. Yield increases will be mainly in northern Europe, and the largest decreases in the Mediterranean, the southwest Balkans, and the south of European Russia.
- Southern European crops such as maize, sunflower, and soybeans will have a northward expansion.
- Mediterranean productivity of crops will be affected by more frequent droughts and dry spells leading to reduced yields (e.g., sunflower), scrublands and deciduous forests, increased water demand for irrigation, higher risk of fire, and less biodiversity.
- Livestock disease risk will increase for diseases such as bluetongue and African horse sickness.
- Forest productivity will increase substantially in northern Europe. There will be soil carbon losses in boreal forests and seasonal shifts in extent of frost damage.

- Grassland productivity in temperate Europe will increase.
- Marine fish and shellfish to be affected in the North Atlantic as shifts in species distribution lead to increased production in northern waters and marked decreases at the southern edge of current ranges where there will be increased stress due to pathogens. Aquaculture will suffer local impacts due to organic wastes and spread of pathogens.

Europe is well watered, with numerous permanent rivers, many of which flow outwards from the central part of the continent. It also has large areas with low relief. The main types of climate in Europe are maritime, transitional, continental, polar, and Mediterranean; the major vegetation types are tundra, coniferous taiga (boreal forest), deciduous–mixed forest, steppe, and Mediterranean. A relatively large proportion of Europe is farmed, with about one-third of the area being classified as arable and cereals being the predominant crops.

The sensitivity of Europe to climate change has a distinct north–south gradient, with many studies indicating that southern Europe will be the more severely affected. The already hot and semiarid climate of southern Europe is expected to become still warmer and drier, threatening its waterways, hydropower, agricultural production, and timber harvests. In Central and Eastern Europe, summer precipitation is projected to decrease, causing higher water stress. Northern countries are also vulnerable to climate change, although in the initial stages of warming there may be some benefits in terms of, for example, increased crop yields and forest growth. Key environmental pressures relate to biodiversity, landscape, soil and land degradation, forest degradation, natural hazards, water management, and recreational environments. Most ecosystems in Europe are managed or semi-managed; they are often fragmented and understress from pollution and other human impacts.

The predicted increase in extreme weather events (e.g., spells of high temperature and droughts) is projected to increase yield variability (Jones et al. 2003) and to reduce average yield. In particular, in the European Mediterranean region, increases in the frequency of extreme climate events during specific crop development stages (e.g., heat stress during the flowering period, rainy days during sowing dates), together with higher rainfall intensity and longer dry spells, are likely to reduce the yield of summer crops (e.g., sunflower).

The expected warmer climate in northern Europe will influence crop production, animal husbandry and animal health, as well as the natural flora and fauna. Crop yields will probably increase in the Nordic region, and it may also be possible to grow new crops for feed and food production. In southern Europe, the warm climate will most likely reduce crop productivity because of drought. Many pests and diseases will also become more prevalent on both animals and plants. People should be prepared for this new situation to be able to minimize the negative effects of climate change while taking advantage of the warmer climate in the region. Increased yields and new crops are expected, but also more pest and disease problems. It is important to increase collaboration in northern Europe in the development of crop protection systems in order to be prepared for new pests and diseases of different crops.

Climate change is perhaps the biggest single issue facing Europe and the rest of the world at the start of the twenty-first century. It is not certain that what climatic conditions one has to face in the coming years, as people are already experiencing the effects of climate change and there will be more significant changes to weather patterns as average global temperatures rise. For many countries in Europe, summers will become hotter and drier, while winter rainfall is likely to rise for many. Warmer, wetter weather in the north will encourage the growth of fungal diseases and pests. Hotter and drier conditions in the south will promote insect infestations accompanied by potential for drought. Already, every 10 months, a new agricultural pest enters Europe from the south, moving north as conditions change.

If the projected 2 °C rise in average temperatures comes to pass, then:

- Southern Europe may become too hot and arid to grow its present crops.
- Northern Europe will be the best place to grow typically Mediterranean crops.

- Scandinavia and Scotland may be prime wine producing areas.
- Much of Siberia will be a major cereal-growing area.
- For even small temperature increases of 1–2°, yields for rainfed agriculture could be reduced by up to 50 % by 2020 (IPCC AR4).

With high confidence, the IPCC (2007) projected that in southern Europe, climate change would reduce crop productivity. In Central and Eastern Europe, forest productivity was expected to decline. In northern Europe, the initial effect of climate change was projected to increase crop yields.

5.4.1 Adaptation and Vulnerability

To adapt to increasing water stress, the most common and planned strategies remain supply-side measures such as impounding rivers to form instream reservoirs. However, new reservoir construction is being increasingly constrained in Europe by environmental regulations and high investment costs. Other supply-side approaches, such as wastewater reuse and desalination, are being more widely considered, but their popularity is dampened, respectively, by health concerns in using wastewater and the high energy costs of desalination. Some planned demand-side strategies are also feasible, such as household, industrial, and agricultural water conservation, reducing leaky municipal and irrigation water systems and water pricing. Irrigation water demand may be reduced by introducing crops that are more suited to a changing climate. An example of a unique European approach to adapting to water stress is that regional- and watershed-level strategies to adapt to climate change are being incorporated into plans for integrated water management, while national strategies are being designed to fit into existing governance structures.

Adaptation procedures and risk management practices for the water sector are being developed in some countries and regions (e.g., the Netherlands, the UK, and Germany) that recognize the uncertainty of projected hydrological changes.

5.5 Latin America

- Food security will be impacted in dry areas where agricultural land will be subject to salinization and erosion, reducing crop yields and livestock productivity.
- Agricultural lands are very likely to be subjected to 50 % desertification and salinization in some areas by the 2050s.
- Crop yields may be reduced in some areas, although other areas may see increases.
- Habitat loss and species extinction in many areas, including tropical forests, due to higher temperatures and loss of groundwater, especially effecting indigenous communities.
- Low-lying areas will be impacted by sea-level rise and extreme events, particularly those associated with the El Niño Southern Oscillation (ENSO) phenomenon which will affect the La Plata estuary, coastal morphology, coral reefs and mangroves, location of fish stocks, and availability of drinking water.

Population growth continues, with consequences for food demand. Because the economies of most Latin American countries depend on agricultural productivity, regional variation in crop yields is a very relevant issue. Latin America has a large variety of climate as a result of its geographical configuration. The region also has large arid and semiarid areas. The climatic spectrum ranges from cold, icy high elevations to temperate and tropical climate. Glaciers have generally receded in the past decades, and some very small glaciers have already disappeared.

The Amazon, the Parana-Plata, and Orinoco together carry into the Atlantic Ocean more than 30 % of the renewable freshwater of the world. However, these water resources are poorly distributed, and extensive zones have very limited water availability. There are stresses on water availability and quality where low precipitation or higher temperatures occur. Droughts that are statistically linked to ENSO events generate rigorous restrictions on the water resources of many areas in Latin America.

As a result of high rainfall and humidity caused by El Niño, several fungal diseases in maize, potato, wheat, and bean are observed in Peru. Some positive impacts are reported for the Argentinean Pampas region, where increases in precipitation led to increases in crop yields close to 38 % in soybean, 18 % in maize, 13 % in wheat, and 12 % in sunflower. In the same way, pasture productivity increased by 7 % in Argentina and Uruguay.

Several studies using crop simulation models, under climate change, for commercial crops, were run for the Latin America region. The number of people at risk of hunger under SRES emissions scenario A2 is projected to increase by one million in 2020, while it is projected that there will be no change for 2050 and that the number will decrease by four million in 2080.

With high confidence, the IPCC (2007) projected that in drier areas of Latin America, productivity of some important crops would decrease and livestock productivity decline, with adverse consequences for food security. In temperate zones, soybean yields were projected to increase.

5.5.1 Adaptation and Vulnerability

5.5.1.1 Past and Current Adaptation

The lack of adequate adaptation strategies to cope with the hazards and risks of floods and droughts in Latin American countries is due to low gross national product (GNP), the increasing population settling in vulnerable areas (prone to flooding, landslides, or drought), and the absence of the appropriate political, institutional, and technological frameworks. Nevertheless, some communities and cities have organized themselves, becoming active in disaster prevention. Many poor inhabitants have been encouraged to relocate from flood-prone areas to safer places. With the assistance of IRDB and IDFB loans, they built new homes, e.g., resettlements in the Paraná River Basin of Argentina, after the 1992 flood. In some cases, a change in environmental conditions affecting the typical economy of the Pampas has led to the introduction of new production activities through aquaculture, using natural regional fish species such as pejerrey (*Odontesthes bonariensis*). Another example, in this case related to the adaptive capacity of people to water stresses, is provided by "self-organization" programs for improving water supply systems in very poor communities. The organization Business Partners for Development Water and Sanitation Clusters has been working on four "focus" plans in Latin America: Cartagena (Colombia), La Paz and El Alto (Bolivia), and some underprivileged districts of Gran Buenos Aires (Argentina). Rainwater cropping and storage systems are important features of sustainable development in the semiarid tropics. In particular, there is a joint project developed in Brazil by the NGO Network Articulação no Semi-Árido (ASA) Project, called the PIMC Project, for one million cisterns to be installed by civilian society in a decentralized manner. The plan is to supply drinking water to one million rural households in the perennial drought areas of the Brazilian semiarid tropics (BSATs). During the first stage, 12,400 cisterns were built by ASA and the Ministry of Environment of Brazil and a further 21,000 were planned by the end of 2004. In Argentina, national safe water programs for local communities in arid regions of Santiago del Estero Province installed ten rainwater catchments and storage systems between 2000 and 2002.

5.5.1.2 Adaptation: Practices, Options, and Constraints

Water management policies in Latin America need to be relevant and should be included as a central point for adaptation criteria. This will enhance the region's capability to improve its management of water availability. Adaptation to drier conditions in approximately 60 % of the Latin America region will need large investments in water supply systems. Managing trans-basin diversions has been the solution in many areas (e.g., Yacambu Basin in Venezuela, Alto Piura and Mantaro Basin in Peru). Water conservation practices, water recycling, and optimization of water consumption have been recommended during water-stressed periods. Problems in education and public health services are fundamental barriers to adaptation, for example, in the case of extreme events (e.g., floods or droughts) mainly in poor rural areas.

5.6 North America

- Rainfed agriculture is likely to increase yields by 5–20 % in the early decades of the century, but with important variability among regions.
- Water resources will be affected by warming in western mountains which will lead to decreased snowpack, more winter flooding, and reduced summer flows, exacerbating competition for over-allocated water resources.
- Crops near the warm end of their suitable range, such as wine grapes, or those that depend on highly utilized water resources will face major challenges.
- Forest growth is likely to increase 10–20 % overall during the twenty-first century as a result of extended growing seasons and CO_2 elevation, although with important spatiotemporal variation. Forests are likely to be affected by changes in disturbances from insects, diseases, and wild fires and associated losses depending on the emission scenario.
- Cold-water fisheries are likely to be negatively affected, while warm-water fisheries will generally gain with mixed results for cool-water fisheries. Higher temperatures will lead to northward shifts of species distribution.

As the rate of warming accelerates during the coming decades, changes can be anticipated in the timing, volume, quality, and spatial distribution of freshwater available for human settlements, agriculture, and industrial users in most regions of North America. While some of the water resource changes listed above hold true for much of North America, twentieth-century trends suggest a high degree of regional variability in the impacts of climate change on runoff, stream flow, and groundwater recharge. Variations in wealth and geography also contribute to an uneven distribution of likely impacts, vulnerabilities, and capacities to adapt in both Canada and the USA.

A number of studies have been produced which assess the impacts of climate change on agriculture in North America. The IPCC Fourth Assessment Report of agricultural impacts in the region cites 26 different studies. With high confidence, the IPCC (2007) projected that over the first few decades of this century, moderate climate change would increase aggregate yields of rainfed agriculture by 5–20 %, but with important variability among regions. Major challenges were projected for crops that are near the warm end of their suitable range or which depend on highly utilized water resources.

Research since the TAR supports the conclusion that moderate climate change will be likely to increase yields of North American rainfed agriculture, but with smaller increases and more spatial variability than in earlier estimates (high confidence) (Reilly et al. 2001). Many crops that are currently near climate thresholds, however, are projected to suffer decreases in yields, quality, or both, with even modest warming (medium confidence).

The vulnerability of North American agriculture to climatic change is multidimensional and is determined by interactions between preexisting conditions, indirect stresses stemming from climate change (e.g., changes in pest competition, water availability), and the sector's capacity to cope with multiple, interacting factors, including economic competition from other regions as well as improvements in crop cultivars and farm management. Water availability is the major factor limiting agriculture in southeast Arizona, but farmers in the region perceive that technologies and adaptations such as crop insurance have recently decreased vulnerability. Areas with marginal financial and resource endowments (e.g., the US northern plains) are especially vulnerable to climate change. Unsustainable land-use practices will tend to increase the vulnerability of agriculture in the US Great Plains to climate change. Heavily utilized groundwater-based systems in the southwest USA are likely to experience additional stress from climate change that leads to decreased recharge (high confidence), thereby impacting agricultural productivity.

Decreases in snow cover and more winter rain on bare soil are likely to lengthen the erosion season and enhance erosion, increasing the potential for water quality impacts in agricultural areas. Soil management practices (e.g., crop residue, no-till) in the North American grain belt may not provide sufficient erosion protection against future intense precipitation and associated runoff.

5.6.1 Adaptation

Although North America has considerable capacity to adapt to the water-related aspects of climate change, actual practice has not always protected people and property from the adverse impacts of floods, droughts, storms, and other extreme weather events. Especially vulnerable groups include indigenous peoples and those who are socially or economically disadvantaged. Traditions and institutions in North America have encouraged a decentralized response framework where adaptation tends to be reactive, unevenly distributed, and focused on coping with rather than preventing problems. Examples of adaptive behavior influenced exclusively or predominantly by projections of climate change and its effects on water resources are largely absent from the literature. A key prerequisite for sustainability in North America is "mainstreaming" climate issues into decision-making.

The vulnerability of North America depends on the effectiveness of adaptation and the distribution of coping capacity; both of which are currently uneven and have not always protected vulnerable groups from the adverse impacts of climate variability and extreme weather events. The USA and Canada are developed economies with extensive infrastructure and mature institutions, with important regional and socioeconomic variation. These capabilities have led to adaptation and coping strategies across a wide range of historical conditions, with both successes and failures. Most studies on adaptive strategies consider implementation based on past experiences.

North American agriculture has been exposed to many severe weather events during the past decade. More variable weather, coupled with outmigration from rural areas and economic stresses, has increased the vulnerability of the agricultural sector overall, raising concerns about its future capacity to cope with a more variable climate. North American agriculture is, however, dynamic. Adaptation to multiple stresses and opportunities, including changes in markets and weather, is a normal process for the sector. Crop and enterprise diversification, as well as soil and water conservation, are often used to reduce weather-related risks.

Many cities in North America have initiated "no regret" actions based on historical experience. Businesses in Canada and the USA are also investing in adaptations relevant to changes in water resources, though few of these appear to be based on future climate change projections. Examples of these types of adaptations include the following:

- Insurance companies are investing in research to prevent future hazard damage to insured property and to adjust pricing models.
- Ski resort operators are investing in lifts to reach higher altitudes and in equipment to compensate for declining snow cover.
- New York has reduced total water consumption by 27 % and per capita consumption by 34 % since the early 1980s.
- In the Los Angeles area, incentive and information programs of local water districts encourage water conservation.
- With highly detailed information on weather conditions, farmers are adjusting crop and variety selection, irrigation strategies, and pesticide applications.
- The city of Peterborough, Canada, experienced two 100-year flood events within 3 years; it responded by flushing the drainage systems and replacing the trunk sewer systems to meet more extreme 5-year flood criteria.
- Recent droughts in six major US cities, including New York and Los Angeles, led to adaptive measures involving investments in water conservation systems and new water supply/distribution facilities.
- To cope with a 15 % increase in heavy precipitation, Burlington and Ottawa, Ontario, employed both structural and nonstructural measures, including directing downspouts to lawns in order to encourage infiltration and increasing depression and street detention storage.
- A population increase of over 35 % (nearly one million people) since 1970 has increased water use in Los Angeles by only 7 %, due largely to conservation practices.
- The Regional District of Central Okanagan in British Columbia produced a water management plan in 2004 for a planning area known as the Trepanier Landscape Unit,

which explicitly addresses climate scenarios, projected changes in water supply and demand, and adaptation options.

5.7 Polar Regions (Arctic and Antarctic)

- Northward movement of species in response to higher temperatures and longer growing season provides opportunities for expansion of agricultural and pastoral activities but with associated vulnerabilities related to invasive species, loss of biodiversity, and the spread of animal-transmitted diseases. An estimated 10–50 % of the tundra could be replaced by scrubland and forests.
- Ecosystems will be affected by temperature increase, decreased sea-ice cover, and shifts in hydrological regimes, leading to detrimental effects on many organisms, including migratory birds, mammals, and higher predators.
- Food security of some subsistence systems will be threatened by changes in ecosystems, decreased transport and market access, and lower-quality drinking water.
- Biodiversity changes and alterations in the distribution and productivity of marine biota will have mainly negative effects at the northern ice edge but will benefit the most important Arctic and sub-Arctic commercial fish stocks, such as cod and herring, south of the ice edge.

Meng et al. (2013) assessed the literature for the polar region (Arctic and Antarctica). With medium confidence, they concluded that the benefits of a less severe climate were dependent on local conditions. One of these benefits was judged to be increased agricultural and forestry opportunities.

Hennessy et al. (2007) reported on how climate change had affected agriculture in Iceland. Rising temperatures had made the widespread sowing of barley possible, which had been untenable 20 years ago. Some of the warming was due to a local (possibly temporary) effect via ocean currents from the Caribbean, which had also affected fish stocks.

5.7.1 Adaptation and Vulnerability

A large amount of the overall vulnerability of Arctic freshwater resources to climate change relate to the abrupt changes associated with solid-to-liquid water-phase changes that will occur in many of the cryospheric hydrological systems. Arctic freshwater ecosystems have historically been able to adapt to large variations in climate, but over protracted periods. The rapid rates of change over the coming century, however, are projected to exceed the ability of some biota to adapt and to result in more negative than positive impacts on freshwater ecosystems.

From a human-use perspective, potential adaptation measures are extremely diverse, ranging from measures to facilitate use of water resources (e.g., changes in ice-road construction practices, increased open-water transportation, flow regulation for hydroelectric production, harvesting strategies, and methods of drinking-water access) to adaptation strategies to deal with increased/decreased freshwater hazards (e.g., protective structures) to reduce flood risks or increase flows for aquatic systems. Strong cultural and/or social ties to traditional uses of water resources by some northern people, however, could complicate the adoption of some adaptation strategies.

5.8 Small Islands

- Agricultural land and thus food security will be affected by sea-level rise, inundation, soil salinization, seawater intrusion into freshwater lenses, and decline in freshwater supply.
- Agricultural production will be affected overall by extreme events.
- Fisheries will be affected by increasing sea surface temperatures, rising sea level, and damage from tropical cyclones. Degradation of coral reefs and bleaching will impact fishing incomes.
- Forests affected by extreme events will be slow to regenerate. Forest cover may increase on some high-latitude islands.
- Habitability and thus sovereignty of some states will be threatened due to reduction in island size or complete inundation.

The TAR (IPCC 2001) noted that Small Island States share many similarities (e.g., physical size, proneness to natural disasters and climate extremes, extreme openness of economies, low risk-spreading and adaptive capacity) that enhance their vulnerability and reduce their resilience to climate variability and change. In spite of differences in emphasis and sectoral priorities on different islands, three common themes emerge.

- All Small Island States National Communications emphasize the urgency for adaptation action and the financial resources to support such action.
- Freshwater is seen as a critical issue in all Small Island States, both in terms of water quality and quantity.
- Many Small Island States, including all of the Small Island Developing States (SIDS), see the need for greater integrated watershed planning and management.

Water is a multi-sectoral resource that links to all facets of life and livelihood, including security. Reliability of water supply is viewed as a critical problem on many islands at present and one whose urgency will increase in the future. There is strong evidence that, under most climate change scenarios, water resources in small islands are likely to be seriously compromised (very high confidence). Most small islands have a limited water supply, and water resources in these islands are especially vulnerable to future changes and distribution of rainfall. The range of adaptive measures considered and the priorities assigned is closely linked to each country's key socioeconomic sectors, its key environmental concerns, and areas most at risk of climate change impacts such as sea-level rise.

Projected impacts of climate change include extended periods of drought and, on the other hand, loss of soil fertility and degradation as a result of increased precipitation, both of which will negatively impact on agriculture and food security. In a study on the economic and social implications of climate change and variability for selected Pacific islands, it was found that, in the absence of adaptation, a high island such as Viti Levu, Fiji, could experience damages of US$23–52 million per year by 2050 (equivalent to 2–3 % of Fiji's GDP in 2002), while a group of low islands such as Tarawa, Kiribati, could face damages of more than US$8–16 million a year (equivalent to 17–18 % of Kiribati's GDP in 2002) under SRES A2 and B2. On many Caribbean islands, reliance on agricultural imports, which themselves include water used for production in the countries of origin, constitutes up to 50 % of food supply.

In a literature assessment, Mimura et al. (2007) concluded that on small islands, subsistence and commercial agriculture would very likely be adversely affected by climate change. This projection was assigned "high confidence."

5.8.1 Adaptation, Vulnerability, and Sustainability

Sustainable development is often stated as an objective of management strategies for small islands. Relatively little work has explicitly considered what sustainable development means for islands in the context of climate change. It has long been known that the problems of small scale and isolation, of specialized economies, and of the opposing forces of globalization and localization may mean that current development in small islands becomes unsustainable in the long term.

While there has been considerable progress in regional projections of sea level since the TAR, such projections have not been fully utilized in small islands because of the greater uncertainty attached to their local manifestations, as opposed to global projections. Reliable and credible projections based on outputs at finer resolution, together with local data, are needed to inform the development of reliable climate change scenarios for small islands. These approaches could lead to improved vulnerability assessments and the identification of more appropriate adaptation options at the scale of islands and across time scales of climatic impacts.

Vulnerability studies conducted for selected small islands show that the costs of infrastructure and settlement protection represent a significant proportion of GDP, often well beyond the financial means of most Small Island States, a problem not always shared by the islands of continental countries. More recent studies have identified major areas of adaptation, including water resources and watershed management, reef conservation, agricultural and forest management, conservation of biodiversity, energy security, increased development of renewable energy, and optimized energy consumption. A framework which considers current and future community vulnerability and involves methodologies integrating climate science, social science, and communication provides the basis for building adaptive capacity. This approach requires community members to identify climate conditions relevant to them and to assess present and potential adaptive strategies. One such methodology was tested in Samoa and results from one village. In this case, local residents identified several adaptive measures including building a seawall, a water-drainage system, water tanks, a ban on tree clearing, some relocation, and renovation to existing infrastructure.

The IPCC AR4 has identified several key areas and gaps that are underrepresented in contemporary research on the impacts of climate change on small islands. These include:

- The role of coastal ecosystems such as mangroves, coral reefs, and beaches in providing natural defenses against sea-level rise and storms.
- Establishing the response of terrestrial upland and inland ecosystems to changes in mean temperature and rainfall and in temperature and rainfall extremes.
- Considering how commercial agriculture, forestry, and fisheries, as well as subsistence agriculture, artisanal fishing, and food security, will be impacted by the combination of climate change and non-climate-related forces.
- Expanding knowledge of climate-sensitive diseases in small islands through national and regional research – not only for vector-borne diseases but for skin, respiratory, and waterborne diseases.
- Given the diversity of “island types” and locations, identifying the most vulnerable systems and sectors, according to island types.

In contrast to the other regions in this assessment, there is also an absence of reliable demographic and socioeconomic scenarios and projections for small islands. The result is that future changes in socioeconomic conditions on small islands have not been well presented in the existing assessments. For example, without either adaptation or mitigation, the impacts of sea-level rise, more intense storms, and other climate change will be substantial, suggesting that some islands and low-lying areas may become unlivable by 2100.

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6 Impacts on Crop Protection

Abstract

Anthropogenically induced climatic change arising from increasing levels of atmospheric greenhouse gases influences the ecology of agricultural pests such as insect pests, diseases, nematodes, and weeds. Changes in climate may trigger changes in geographical distribution, increased overwintering, changes in population growth rates, increases in the number of generations, extension of the development season, changes in crop–pest synchrony, changes in interspecific interactions, pest biotypes, activity and abundance of natural enemies, species extinction, increased risk of invasion by migrant pests, and efficacy of crop protection technologies. Global warming will also reduce the effectiveness of host plant resistance, transgenic plants, natural enemies, biopesticides, and synthetic chemicals for pest management. Therefore, there is a need to generate information on the likely effects of climate change on pests to develop robust pest management technologies that will be effective in future under global warming and climate change.

Keywords

Climate change • Insects • Mites • Plant pathogens • Nematodes • Weeds

Crop plants live in a very complex ecosystem in competition with neighboring plants including weeds. Both are supported and/or attacked by viruses, bacteria, fungi, insects, mites, spiders, nematodes, amphibia, birds, mammals etc. All of these species interact with each other. It is estimated that globally 70,000 pest species, including 9,000 insect and mites, 50,000 plant pathogens, and 8,000 species of weeds, exist. About 10 % of these 70,000 are considered major pests. Climate change will increase the challenges from pests.

There have been several efforts to provide a measure of global crop losses by weeds, insects, and diseases. The most recent and comprehensive of these estimates are those made by Oerke (2006) (Table 6.1). Estimates on potential and actual losses despite the current crop protection practices are given for wheat, rice, maize, potatoes, soybeans, and cotton for the period 2001–

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Table 6.1 Estimated potential of weeds, animal pests (arthropods, nematodes, rodents, birds, snails, and slugs), pathogens (fungi and bacteria), and viruses due to pest groups in six major crops worldwide, in 2001–2003 (Oerke 2006)

Crop	Attainable production (million tons)	Crop losses (%) due to				
		Weeds	Animal pests	Pathogens	Viruses	Total
Wheat	785.0	23.0	8.7	15.6	2.5	49.8
Rice	933.1	37.1	24.7	13.5	1.7	77.0
Maize	890.8	40.3	15.9	9.4	2.9	68.5
Potatoes	517.7	30.2	15.3	21.2	8.1	74.9
Soybeans	244.8	37.0	10.7	11.0	1.4	60.0
Cotton	78.5[a]	35.9	36.8	8.5	0.8	82.0

[a] Seed cotton

2003 on a regional basis (19 regions) as well as for the global total. Among crops, the total global potential loss due to pests varied from about 50 % in wheat to more than 80 % in cotton production. The responses are estimated as losses of 26–29 % for soybean, wheat, and cotton and 31, 37, and 40 % for maize, rice, and potatoes, respectively. Overall, weeds produced the highest potential loss (34 %), with animal pests and pathogens being less important (losses of 18 and 16 %). The efficacy of crop protection was higher in cash crops than in food crops. Weed control can be managed mechanically or chemically; therefore, worldwide efficacy was considerably higher than for the control of animal pests or diseases, which rely heavily on synthetic chemicals. Despite a clear increase in pesticide use, crop losses have not significantly decreased during the last 40 years. However, pesticide use has enabled farmers to modify production systems and to increase crop productivity without sustaining the higher losses likely to occur from an increased susceptibility to the damaging effect of pests.

Nationally, pests are estimated to destroy about one-third of our crops and are an increasingly serious constraint to crop production, in spite of the advances in pest control technology over the last half century.

Agricultural trends are influencing the incidence and importance of pests. First, the expansion of worldwide trade in food and plant products is spreading the impact of weeds, insects, and diseases. Second, changes in cultural techniques, particularly intensification of cropping, reduction in crop rotations, and increase in monocultures, encourage the activity of pests.

Many people believe that global warming as predicted would increase pressure from weeds, pests, and diseases. Higher temperatures and longer growing seasons could result in increased pest populations in temperate regions of Asia. Warmer winter temperatures would reduce winter kill, favoring the increase of insect populations. Overall temperature increases may influence crop pathogen interactions by speeding up pathogen growth rates which increases reproductive generations per crop cycle, by decreasing pathogen mortality due to warmer winter temperatures and by making the crop more vulnerable (Cruz et al. 2007).

Climate change will affect crop protection challenges. In cooler latitudes, global warming brings new species but others may disappear. Whether or not new species translate into pest problems is uncertain. Invasive species are often brought to other places by global trade of food and goods.

Climate change might have an influence on pesticide use due to presence of weeds, diseases, pests, and their natural enemies. The latter factors are influenced by the weather and in the midterm by climatic changes (Goudriaan and Zadoks 1995). Tilman et al. (2001) foresee a 2.4–2.7-fold increase in pesticide use by 2050. Chen and McCarl (2001) investigated the relationship of temperature, precipitation, and pesticide costs for several crops in the USA and concluded that increases in rainfall lead to increases in average pesticide costs for corn, cotton, potatoes, soybeans, and wheat, while hotter weather increases pesticide costs for corn, cotton, potatoes, and soybeans but decreases the cost for wheat.

Table 6.2 Serious crop pest epidemics critically influenced by climate change

Event effects	Pest damage to crops
Floods and heavy rains	Increased moisture benefits epidemics and prevalence of fungal leaf pathogens
	Rice leaf blight caused great famine in Bengal (1942), two million people died
	Wheat stripe rust outbreak in major production regions of China contributed to the 1960s famine
	Fungal epidemics in corn, soybean, alfalfa, and wheat in the US Midwest (1993)
	Mycotoxin produced by wheat scab (*Fusarium* spp.) reached a record high in the US Great Plains (1993)
	Humid summers drive epidemics of gray leaf spot of maize in Iowa and Illinois (1996)
	Water-induced soil transport increases dissemination of soilborne pathogens to noninfected areas
	Outbreaks of soybean sudden death syndrome in the north central US states (1993)
	Continuous soil saturation causes long-term problems related to rot development and increase damage by diseases
	Crazy top and common smut in maize
Drought	Water stress diminishes plant vigor and alters carbon-to-nitrogen ratios, lowering plant resistance to nematodes and insects. Attack by fungal pathogens of stems and roots is favored by weakened plant conditions. Drought promotes insect outbreaks
	Outbreak of soybean cyst nematode correlated to drought conditions in the north central US states (1990)
	Summer locust outbreak correlated to drought in Mexico (1999)
	Dry and warm conditions promote growth of insect vector populations, increasing viral epidemics
Storms and air currents	Air currents provide large-scale transportation for disease agents (e.g., spores of fungi) or insects from overwintering areas to attacking areas
	The spread of the stem rust fungus that overwinters in Mexico and Texas is always favored by moist southern air currents
	The southern leaf blight of corn spread from Mississippi to the Midwest by air currents of a tropical storm in the Gulf of Mexico during 1970
Warm winters	Warm winters increase overwintering populations of all pests
	Data reported for the European corn borer, wheat scab, and wheat rust
	Increase overwintering populations of insect vectors
	Increase population of aphids that carry the soybean mosaic virus

In addition, increased atmospheric carbon dioxide is expected to alter the nutritional makeup of crops, thereby affecting the severity of attack from insects and disease organisms (Coviella and Trumble 1999).

In general, however, most pest species are favored with warm and humid conditions. Pest infestations often coincide with changes in climatic conditions, such as early or late rains, drought, or increases in humidity, which, in themselves, can reduce yields (Table 6.2).

6.1 Weeds

Worldwide, weeds have been estimated to cause annual crop production losses of about 12 % (Oerke et al. 1994). In the USA, annual losses in crop production due to weeds have been valued at approximately US$ 12 billion, amounting to some 10 % of potential production. Large efforts are made to limit these damages through a variety of weed control measures.

Around the world, more human labor is expended in hand weeding than in any other agricultural task, and most cultivation and tillage practices are designed to aid in weed control. The chemical industry manufactures herbicides, which, next to fertilizers, account for the largest volume of chemicals applied to crops. Over US$ 9 billion are spent on weed control every year in the USA (USDA 1999).

Weeds, which are better adapted to arid conditions than crops, will provide increased competition for moisture, nutrients, and light. Herbicidal controls are less effective under hot and dry conditions, but mechanical cultivation is more effective (Pimentel et al. 1991). Another problem with herbicides applied under arid conditions is that they accumulate in the soil, which can lead to serious environmental problems.

Overall, US crop losses due to weeds are projected to rise from 5 to 50 % for selected crops. Similarly, warm and moist conditions projected for Africa are expected to increase crop losses due to pests (Pimentel et al. 1993).

Elevated CO_2, changes in temperature, and precipitation patterns may affect weeds as much as crops. Higher CO_2 will stimulate photosynthesis and growth in C3 weeds and C3 crops and reduce transpiration and increase water-use efficiency in both C3 and C4 weeds and crops. Higher temperatures can possibly offset some of the benefits of elevated CO_2 for both weeds and crops. High temperatures sometimes limit reproductive development and global warming may decrease reproductive output in such situations despite an increase in CO_2. It is unclear whether this is more likely to occur in C3 than C4 species, but if it were, it could alter weed community compositions and affect crop–weed interactions (Bunce and Ziska 2000).

This would imply that weeds and crops both benefit or lose on the same scale. However, weeds are usually already very competitive due to greater genetic variation and physiological plasticity; otherwise, they would not cause yield losses. Hence, they may gain more advantages from climate change than crops (Bunce and Ziska 2000).

In temperate regions, global warming will affect the growth and marginally affect phenology and influence the geographical distribution of weeds. Weed species of tropical and subtropical origins, currently restricted to the southern regions, may expand northwards (Patterson 1995).

6.2 Insect Pests

Insect pests in agricultural systems are the major cause of damage to yield quantity. Insect habitats and survival strategies are strongly dependent on patterns of climate. Insects are particularly sensitive to temperature because they are stenotherm (cold blooded). In general, insects respond to higher temperature with increased rates of development and with less time between generations. Warmer winters reduce winterkill and consequently induce increased insect populations in the subsequent growing season.

Precipitation – whether optimal, excessive, or insufficient – is a key variable that also affects crop–pest interactions. Drought stress sometimes brings increased insect pest outbreaks. It is well known that drought can change the physiology of host species, leading to changes in the insects that feed on them. Abnormally cool, wet conditions can also bring on severe insect infestations, although excessive soil moisture may drown out soil-residing insects.

If global warming raises the temperature by 2 °C in the USA and slightly less in Africa, insects will multiply and prosper. During a growing season, some insects produce 500 offsprings per female every 2 weeks. Rising temperatures will lengthen the breeding season and increase the reproductive rate. That, in turn, will raise the total number of insects attacking a crop and subsequently increase crop losses. In addition, some insects, such as the southwestern corn borer, will be able to extend their range northwards as a result of the warming trend (Chippendale 1979).

Under the projected warming trend in the USA, farmers can expect a 25–100 % increase in losses due to insects, depending on the crop (Pimentel et al. 1993). Because crop losses to insects in Africa are already high, the projected impacts on different crops range from minus 30 % for soybeans to plus 7 % for rice. West Africa's warm, moist conditions are ideal for insects.

Climate change is associated with warming, elevated CO_2 and regionally changed precipitation. Currano et al. (2008) conclude that global warming will in the long term increase insect herbivory. Global warming might therefore benefit many insect species in the temperate regions. A warmer climate in these regions may result in changes in geographical distribution, increased overwintering (i.e., more insects survive the winter), changes in population growth rates, increases in the number of generations, extension of the development season, changes in crop–pest synchrony, changes in interspecific interactions, and increased risk of invasion by migrant pests (Bale et al. 2002).

Under elevated CO_2, population densities of chewing insects are unaffected or decrease, but do not increase while sap sucker (phloem feeder) population densities might increase.

A meta-analysis of studies on elevated temperature and elevated CO_2 suggests that insect herbivore performance is adversely affected by elevated CO_2, favored by elevated temperature, and not modified when both parameters (temperature and CO_2 combined) were elevated.

6.3 Plant Diseases

Climate factors that influence the growth, spread, and survival of crop diseases include temperature, precipitation, humidity, dew, radiation, wind speed, circulation patterns, and the occurrence of extreme events. Higher temperature and humidity and greater precipitation result in the spread of plant diseases, as wet vegetation promotes the germination of spores and the proliferation of fungi and bacteria and influences the lifecycle of soil nematodes. In regions that suffer aridity, however, disease infestation lessens, although some diseases (such as the powdery mildews) thrive in hot, dry conditions, as long as there is dew formation at night.

Under the warmer-but-drier conditions projected for North America, crop losses due to plant diseases are expected to decline as much as 30 %. However, under the wetter conditions projected for Africa, losses from diseases will increase by more than 100 % for some crops.

6.4 Nematodes

Herbivore nematodes feed on plant parts mostly on roots. It is estimated that nematodes cause crop losses worth US$ 125 billion annually in agriculture (Chitwood 2003).

Climate change due to increased emission of greenhouse gases is posing a serious challenge to sustainability of crop production by interfering with biotic and abiotic components and their interactions with each other. Global warming resulting in elevated carbon dioxide (CO_2) and temperature in the atmosphere may influence plant pathogenic nematodes directly by interfering with their developmental rate and survival strategies and indirectly by altering host plant physiology. Severe droughts resulting in a reduction of soil water will most likely negatively affect soil nematodes.

Nematode developmental rate is directly influenced by the temperature with slower development at cooler and faster growth rate at warmer soil temperatures. Therefore, increase in atmospheric temperature due to global warming is expected to result in more number of generations per season and expansion of their geographical distribution range. Other potential effects of elevated temperature on parasitic nematodes include altered sex ratio, host defense responses, and interference in their survival strategies like dauer juveniles or egg diapauses in extreme environments.

Herbivorous nematodes showed neutral or positive response to CO_2 enrichment effects with some species showing the potential to build up rapidly and interfere with plant's response to global warming. The number of herbivore, bacterivore, and fungivore nematodes was significantly higher under winter wheat and sugar beets grown under elevated CO_2 (550 ppm), while the number of carnivore was not changed. The total numbers of herbivore, bacterivore, and fungivore nematodes were higher under elevated CO_2 wheat than under elevated CO_2 sugar beet, most likely due to the very different root system of both plant species (Sticht et al. 2009).

6.5 Adaptation and Mitigation

Adaptation refers to an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects that moderate, harm, or exploit beneficial opportunities.

Climate change mitigation encompasses the actions being taken, and those that have been proposed, to limit the magnitude and/or rate of long-term global warming-induced climate change.

- Biosecurity, quarantine, monitoring, and control measures can be strengthened to control the spread of pests and diseases under a warming climate.
- More resilient/adaptable crop genotypes needed, especially with durable resistance to pests.
- Adoption of environmental conserving pest control activities such as organic farming, biocontrol, and integrated (ecological) pest management.
- Application of natural mulches helps in suppression of harmful pests and diseases.
- A diverse fauna of natural enemy species can successfully suppress pests.
- Mulching and reduced tillage, for example, increases spider abundance.
- Specific relationships between pests and host plants are interrupted by crop rotations.
- A "healthy" soil, with optimal physical, chemical, and biological properties, increases plant resistance to insects and diseases.
- Avoidance of excess use of nitrogen which can increase the severity of certain diseases and make a crop more susceptible to pests.
- Organic agriculture system uses crop rotation, green manure, compost, biological pest control, and mechanical cultivation to control pests. Organic systems avoid the use of synthetic pesticides and rely on cultural practices such as crop rotations which break up pest cycles and encourage beneficial insects.
- Polyculture techniques such as crop rotation, multi-cropping, and intercropping are less susceptible to pests than monoculture crops.
- In addition to the prudent application of pesticides, increased use of nonchemical pest controls (crop rotations, biological controls, altering planting dates and fertilizer and irrigation applications, and soil management and tillage) would help minimize crop losses and thereby help maintain crop yields.
- Genetically engineered plants have been designed to resist pests, diseases, and nematodes without the need for pesticides.
- The growers of the crops have to change pest management strategies by rescheduling the crop calendars in accordance with the projected changes in pest incidence and extent of crop losses in view of the changing climate.
- Geographic Information System (GIS) is an enabling technology for crop protection scientists, which help in relating pest outbreaks to biographic and physiographic features of the landscape, hence can best be utilized in area wide pest management programs.
- Pesticides with novel mode of actions such as neonicotinoid insecticides for controlling sucking pests which induces salicylic acid-associated plant defense responses. Such more compounds need to be identified for use in future crop pest management.
- Integrated pest management (IPM) is an effective and environmentally sensitive approach to pest management that uses current, comprehensive information on the life cycles of pests and their interaction with the environment to manage pest damage by the most economical means and with the least possible hazard to people, property, and the environment.

6.6 Conclusions

Global warming and climate change will have serious consequences on diversity and abundance of pests and the extent of losses due to pests, which will impact both crop production and food security. Prediction of changes in geographical distribution and population dynamics of pests will be useful to adapt the pest management strategies to mitigate the adverse effects of climate change on crop production. Pest outbreaks might occur more frequently, particularly during extended periods of drought, followed by heavy rainfall. Some of the components of pest management such as host plant resistance, biopesticides, natural enemies, and synthetic chemicals will be rendered less effective as a result of increase in temperatures and UV radiation and decrease in relative humidity. Climate change will also alter the interactions between the pests and their host plants. As a result, some of the cultivars that are resistant to pests may exhibit susceptible reaction under global warming. Adverse effects of climate change on the activity and effectiveness of natural enemies will be a major concern in future pest management programs. Rate of pest multiplication might increase with an increase in CO_2 and temperature. Therefore, there is a need to have a concerted look at the likely effects of climate change on crop protection and devise appropriate measures to mitigate the effects of climate change on food security.

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7 Impacts on Insect and Mite Pests

Abstract

The occurrence of climate changes is evident from increase in global average temperature, changes in the rainfall pattern, and extreme climatic events. Climate and weather can substantially influence the fauna, flora, population dynamics development, and distribution of insects. Anthropogenically induced climatic change arising from increasing levels of atmospheric greenhouse gases would, therefore, be likely to have a significant effect on agricultural insect pests. Current best estimates of changes in climate indicate an increase in global mean annual temperatures of 1 °C by 2025 and 3 °C by the end of the next century. Such increases in temperature have a number of implications for temperature-dependent insect pests in midlatitude regions. Changes in climate may result in changes in geographical distribution, increased overwintering, changes in population growth rates, increases in the number of generations, extension of the development season, changes in crop–pest synchrony, changes in interspecific interactions, and increased risk of invasion by migrant pests.

Impacts of climate change on crop production mediated through changes in populations of serious insect pests need to be given careful attention for planning and devising adaptation and mitigation strategies for future pest management programs. Therefore, there is a need to have a concerted look at the likely effects of climate change on insect pests and devise appropriate measures to mitigate the effects of climate change on food security.

Keywords

Climate change • Insects • Mites • Population dynamics • Geographical distribution • Winter survival • Impact models

Crop plants used as a food by human beings are damaged by over 10,000 species of insects and cause an estimated annual loss of 13.6 % globally (Benedict 2003). Damage by insect pests is usually caused by chewing on plant tissues or sucking the plant sap (e.g., aphids). In many cases, insect pests also transmit viruses, which then affect the plant.

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7.1 Crop Losses

Insect pests in agricultural systems are the major cause of damage to yield quantity. The most recent and comprehensive efforts to provide a measure of global crop losses by insects are those made by Oerke (2006) (Table 7.1). The estimate of preharvest loss caused by animal pests to the principal food and cash crops is 18 % of potential production on a global basis (Oerke 2006). This high loss to pests is not uniform over space and time, being proportionally higher in Africa and under climate conditions favorable to pests.

Agricultural trends are influencing the incidence and importance of pests. First, the expansion of worldwide trade in food and plant products is spreading the impact of insects. Second, changes in cultural techniques, particularly intensification of cropping, reduction in crop rotations, and increase in monocultures, encourage the activity of insect pests.

In North America, the average losses to insects estimated for 1988–1990 are 13 % of the potential crop value. Among pesticides used for the management of pests, insecticides account for 22 % (US$ 9 billion in 1997) (USDA 1999).

In India, the average annual losses have been estimated to be 17.5 % valued at US$ 17.28 billion in nine major field crops (cotton, rice, maize, sugarcane, rapeseed–mustard, groundnut, pulses, coarse cereals, and wheat) (Dhaliwal et al. 2010). Pest damage varies considerably in different agroclimatic regions across the country mainly due to differential impacts of several abiotic factors such as temperature, humidity, and rainfall (Reed and Pawar 1982; Sharma et al. 2010). This has major implication for the intensification of yield losses due to potential changes in crop diversity and increased incidence of insect pests in the context of impending climate change.

Table 7.1 Estimated potential of animal pests (arthropods, nematodes, rodents, birds, snails, and slugs) and actual losses due to pests in six major crops worldwide, in 2001–2003 (Oerke 2006)

Crop	Attainable production (million tons)	Crop losses (%) due to animal pests	
		Potential	Actual
Wheat	785.0	8.7 (7–10)	7.9 (5–10)
Rice	933.1	24.7 (13–26)	15.1 (7–18)
Maize	890.8	15.9 (12–19)	9.6 (6–19)
Potatoes	517.7	15.3 (14–20)	10.9 (7–13)
Soybeans	244.8	10.7 (4–16)	8.8 (3–16)
Cotton	78.5[a]	36.8 (35–41)	12.3 (5–22)

[a]Seed cotton

7.2 Climate Change and Insect Pests

Losses due to insect damage are likely to increase as a result of changes in crop diversity and increased incidence of insect pests due to global warming. Current estimates of changes in climate indicate an increase in global mean annual temperatures of 1 °C by 2025 and 3 °C by the end of the next century. The date at which an equivalent doubling of CO_2 will be attained is estimated to be between 2025 and 2070, depending on the level of emission of greenhouse gases (IPCC 1990a, b). Mean annual temperature changes between 3 and 6 °C are estimated to occur across Europe, with greatest increases occurring at high latitudes.

Pest menace under the influence of climatic factors, at various stages of crop growth, is one of the factors limiting agricultural productivity (Oerke et al. 1994). Climate is an important determinant of abundance and distribution of species. The rising concentrations of CO_2 will have a variety of direct effects on plants and may also have indirect effects on herbivores and their natural enemies. The climate has profound effects on the populations of invertebrate pests like insects, mites, and others and affects their development, reproduction, and dispersal systems. Extreme weather events such as intense rainstorms, high wind, or elevated temperatures also affect their survival. The climate change impacts on pests may include shifts in species distributions with species shifting their ranges to higher latitudes and elevations, changes in phenology with life cycles beginning earlier in spring and continuing later in autumn, increase in population growth rates and number of generations, change in migratory behavior, alterations in crop–pest synchrony and natural enemy–pest interaction, and changes in interspecific interactions (Root et al. 2003). Changes in community structure and extinction of some species are also expected (Thomas et al. 2004).

For species to survive in the changing climates, they must either adapt in situ to new conditions or shift their distributions in pursuit of more favorable ones. Many insects have large population sizes and short-generation times, and their phenology, fecundity, survival, selection, and habitat use can respond rapidly to climate change. These changes to insect life history may in turn produce rapid changes in their abundance and distribution. Due to recent climate changes, widespread, generalist species at their cool range margins have expanded their distribution ranges, whereas the ranges of localized, habitat-specialist species and those at their warm margins have narrowed (Konvicka et al. 2003). An array of methods including surveys, experiments, and modeling have been used to study the impact of climate change on pest abundance and distribution.

Insect pests of crop plants are the real candidates most affected by global climate change. Complex physiological effects exerted by the increasing temperature and CO_2 may affect profoundly the interactions between crop plants and insect pests (Roth and Lindroth 1995). It has been reported that global climate warming may lead to altitude-wise expansion of the geographic range of insect pests (Elphinstone and Toth 2008), increased abundance of tropical insect species (Bale et al. 2002; Diffenbaugh et al. 2008), decrease in the relative proportion of temperature-sensitive insect population (Petzoldt and Seaman 2010; Sharma et al. 2005, 2010), more incidence of insect-transmitted plant diseases through range expansion, and rapid multiplication of insect vectors (Petzoldt and Seaman 2010). Thus, with changing climate, it is expected that the growers of crops have to face new and intense pest problems in the years to come.

The climate change-led changes in insect pest status will perilously affect agricultural production and the livelihood of farmers in the country where larger portion of work force is directly dependent on climate-sensitive sectors such as agriculture (Chahal et al. 2008). This envisages an urgent need to modify crop protection measures with changed climate in order to attain the goal of food security of the nation.

Insects being poikilotherms, temperature is probably the single most important environmental factor influencing their behavior, distribution, development, survival, and reproduction (Bale et al. 2002; Petzoldt and Seaman 2010). Therefore, it is highly expected that the major drivers of climate change, i.e., elevated CO_2, increased temperature, and depleted soil moisture, can impact population dynamics of insect pests (Fig. 7.1) and the extent of crop losses significantly (Petzoldt and Seaman 2010).

High mobility and rapid population growth will increase the extent of losses due to insect pests. Many species may have their diapause strategies disrupted as the linkages between temperature and moisture regimes, and the day length will be altered. Genetic variation and multifactor inheritance of innate recognition of environmental signals may mean that many insect species will have to adapt readily to such disruption.

Global warming and climate changes will result in:

- Rising temperatures extend geographical range of insect pests.
- Increased overwintering and rapid population growth.
- Changes in insect–host plant interactions.
- Increased risk of invasion by migrant pests.
- Impact on arthropod diversity and extinction of species.
- Changes in synchrony between insect pests and their crop hosts.
- Introduction of alternative hosts as green bridges.
- Reduced effectiveness of crop protection technologies.
- Increase in pesticide sprays.
- Faster resistance to pesticides.

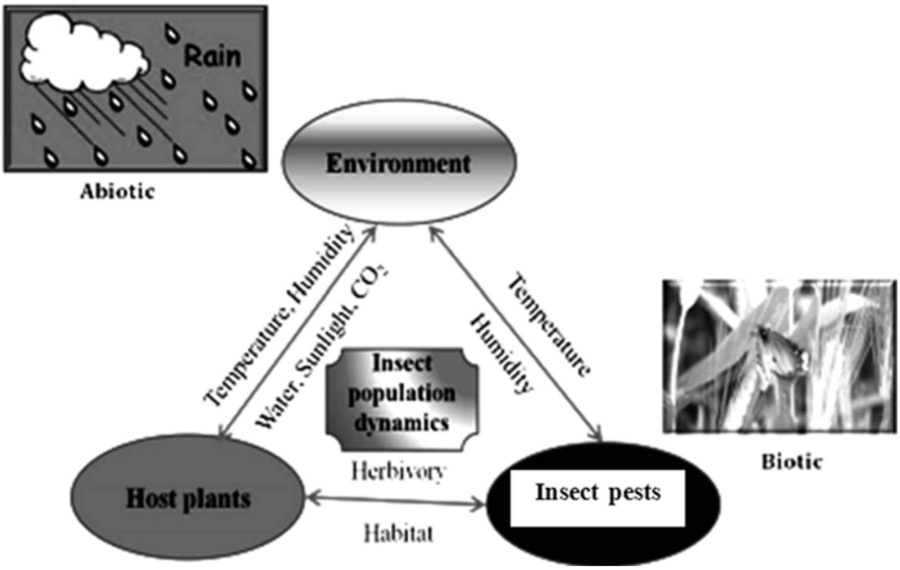

Fig. 7.1 Crop–pest–environment triangle showing interactions between abiotic and biotic factors

- Rising winter temperatures reduce winter mortality.
- Decreased snow cover can increase mortality.
- Rising temperatures extend the growing season.
- Greater nutrient demands coincide with planting and fruiting of many crops.
- Rising temperatures accelerate insect life cycles – greater generation numbers.
- Earlier migration and maturation.

Climate change will also result in increased problems with insect-transmitted diseases. These changes will have major implications for crop protection and food security, particularly in the developing countries, where the need to increase and sustain food production is most urgent. Long-term monitoring of population levels and insect behavior, particularly in identifiably sensitive regions, may provide some of the first indications of a biological response to climate change. In addition, it will also be important to keep ahead of undesirable pest adaptations, and therefore, it is important to carefully consider global warming and climate change for planning research and development efforts for pest management and food security in the future.

7.3 Elevated Temperatures

Insects are cold-blooded organisms, the temperature of their bodies is approximately the same as that of the environment. Therefore, temperature is probably the single most important environmental factor influencing insect behavior, distribution, development, survival, and reproduction (Fig. 7.2). Insect life stage predictions are most often calculated using accumulated degree days from a base temperature and biofix point. Some researchers believe that the effect of temperature on insects largely overwhelms the effects of other environmental factors (Bale et al. 2002). It has been estimated that with a 2 °C temperature increase, insects might experience one to five additional life cycles per season (Yamamura and Kiritani 1998).

In colder regions (higher latitudes) with distinctive seasons, insects have broader thermal tolerance and are living in climates that are currently cooler than their optima (Deutsch et al. 2008). Global warming might therefore benefit many insect species in the temperate regions.

Reduced winter mortality of two insect pests was observed in Japan, when mean temperature in January was above 4 °C. Species which already develop at low temperatures and need a smaller

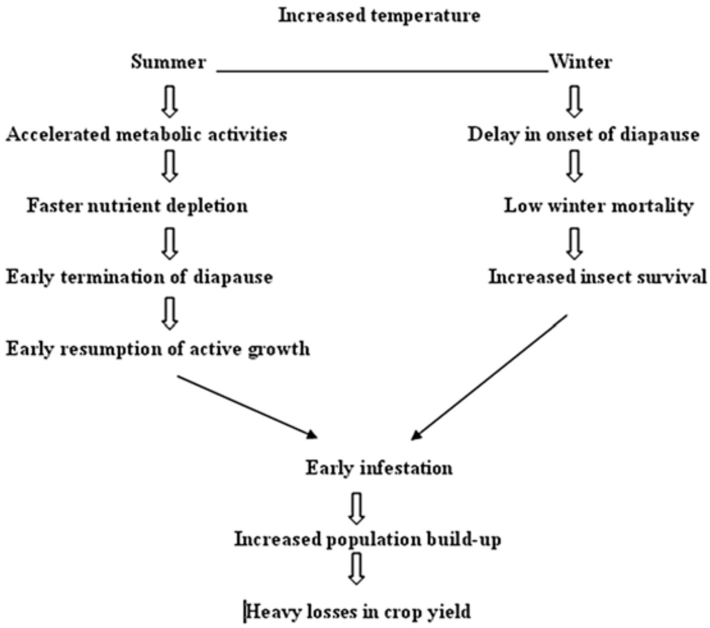

Fig. 7.2 Impact of increased temperature on insect population buildup

Table 7.2 Expected responses of Heteroptera species and communities under two scenarios of further climate change (Musolin 2007)

Categories of responses	Slight temperature increase (<2 °C)	Substantial temperature increase (>2 °C)
Distribution range	Likely to shift in some species, especially those capable of long-distance flights and associated with ornamental plants and/or urban habitats	Likely to shift in many species
Abundance	Likely to increase in multivoltine species with flexible life cycles	Likely to change, depending on the community response
Phenology	Slight to moderate advance of early-season events	Substantial advance of early season and some delay of late season events
Voltinism	An additional generation in some multivoltine species with flexible life cycles	One or more additional generation(s) in some multivoltine and univoltine species (with facultative diapause)
Physiology and behavior	Slight/undetectable changes	Evident/detectable changes (e.g., in parameters of photoperiodic responses)
Community structure	Similar to currently observed	Increased species richness; substantial changes in structure

number of warm days will benefit from increasing average temperatures and produce more generations and appear early when spring temperatures are high. Species which require higher temperature before they lay their eggs tend to have increased reproductive activity.

Musolin (2007) concludes that warming in temperate regions may have manifold effects on bugs. Table 7.2 shows the responses on bugs (Heteroptera) to slight and substantial temperature increases compiled by Musolin (2007).

Studies on aphids and moths have shown that increasing temperatures can allow insects to reach their minimum flight temperature sooner, aiding in increased dispersal capabilities (Zhou et al. 1995). Increased temperatures will accelerate the development of cabbage maggot, onion maggot, European corn borer, and Colorado potato beetle – possibly resulting in more generations (and crop damage) per year.

Lower winter mortality of insects due to warmer winter temperatures could be important in increasing insect populations (Harrington et al. 2001). Higher average temperature might result in some crops being able to be grown in regions further north – it is likely that at least some of the insect pests of those crops will follow the expanded crop areas. Insect species diversity per area tends to decrease with higher latitude and altitude (Andrew and Hughes 2005), meaning that rising temperatures could result in more insect species attacking more hosts in temperate climates (Bale et al. 2002). Bale et al. (2002) concluded that the diversity of insect species and the intensity of their feeding have increased historically with increasing temperature.

Positive physiological responses to increasing temperatures will allow for faster insect growth and movement. Additionally, milder winters will allow for earlier insect growth and a reduction in overwinter deaths. The expansion or shift in ranges coupled with an increase in growth and numbers will likely result in an increase in insect invasions.

Global warming will lead to earlier infestation by *Heliothis zea* in North America (EPA 1989) and *Helicoverpa armigera* in North India (Sharma et al. 2010), resulting in increased crop loss. Rising temperatures are likely to result in availability of new niches for insect pests.

An increase of 3 °C in mean daily temperature would cause the carrot fly, *Delia radicum*, to become active a month earlier than at present (Collier et al. 1991), and temperature increases of 5–10 °C would result in completion of four generations each year, necessitating adoption of new pest control strategies.

As stated earlier the temperature being the single most important regulating factor for insects (Yamamura and Kiritani 1998; Bale et al. 2002; Petzoldt and Seaman 2010), global increase in temperature within certain favorable range may accelerate the rates of development, reproduction, and survival in tropical and subtropical insects. Consequently, insects will be capable of completing more number of generations per year, and ultimately, it will result in more crop damage (Yamamura and Kiritani 1998; Petzoldt and Seaman 2010).

The impacts of climate change on seasonability of insects have been studied by many workers (Bale et al. 2002). The studies showed that declined survival rate of brown planthopper, *Nilaparvata lugens*, and rice leaf folder, *Cnaphalocrocis medinalis*, at higher temperature indicates the impacts of rising temperature could do the changes in the pest population dynamics of rice ecosystem.

Changes in temperature may have highly nonlinear effects on tritrophic interactions of host, pathogen, and biocontrol agent. In wheat (152), a rise in temperature from 17 to 22 °C resulted in an increase in aphid (*Sitobion avenae*) reproduction by 10 %; at the same time, however, predatory activity by lady beetle (*Coccinella septempunctata*) adults increased by 250 %. Aphid damage was reduced further because of earlier maturity of the crop.

Climate change resulting in increased temperature could impact crop–pest insect populations in several complex ways. Although some climate change temperature effects might tend to depress insect populations, most researchers seem to agree that warmer temperatures in temperate climates will result in more types and higher populations of insects.

Researchers have shown that increased temperatures can potentially affect insect survival, development, geographic range, and population size. Temperature can impact insect physiology and development directly or indirectly through the physiology or existence of hosts. Depending on the development "strategy" of an insect species, temperature can exert different effects (Bale et al. 2002). Some insects take several years to complete one life cycle – these insects (cicadas, arctic moths) will tend to moderate temperature variability over the course of their life history. Some crop–pests are "stop and go" developers in relation to temperature – they develop more rapidly during periods of time with suitable temperatures. We often use degree-day or phenology-based models to predict the emergence of these insects and their potential to damage crops (cabbage maggot, onion maggot, European corn borer, Colorado potato beetle). Increased temperatures will accelerate the development of these types of insects – possibly resulting in more generations (and crop damage) per year.

"Migratory" insects (corn earworm in northern parts of the northeast) may arrive in the Northeast earlier, or the area in which they are able to overwinter may be expanded. Natural enemy and host insect populations may respond differently to changes in temperature. Parasitism could be reduced if host populations emerge and pass through vulnerable life stages before parasitoids emerge. Hosts may pass though vulnerable life stages more quickly at higher temperatures, reducing the window of opportunity for parasitism. Temperature may change gender ratios of some pest species such as thrips (Lewis 1997) potentially affecting reproduction rates. Insects that spend important parts of their life histories in the soil may be more gradually affected by temperature changes than those that are aboveground simply because soil provides an insulating medium that will tend to buffer temperature changes more than the air (Bale et al. 2002).

A few pest species/groups have been investigated more thoroughly and the cotton bollworm/pod borer (*Helicoverpa armigera*), a widely occurring lepidopteron pest, might give some idea what impact climate change might have on this species. Larvae of *H. armigera* feed on many vegetables, cotton, and cereals (CPC 2007). The adult moth lays eggs on the plant, and after the eggs are hatched, the caterpillars feed. The duration of larval development depends on the temperature (to a maximum of 35 °C in South and Southeast Asia) and on the quality of the host food. On completion of growth, the fully fed larva enters the soil to pupate. The pupal diapause is induced by short day lengths (11–14 h/day) and low temperatures (15–23 °C) experienced as a larva (CPC 2007). After a number of days, depending on the environmental conditions, the butterfly will emerge from the pupae and the cycle begins again.

Some insects are closely tied to a specific set of host crops. Temperature increases that cause farmers not to grow the host crop any longer would decrease the populations of insect pests specific to those crops. The same environmental factors that impact pest insects can impact their insect predators and parasites as well as the disease organisms that infect the pests, resulting in increased attack on insect populations. At higher temperatures, aphids have been shown to be less responsive to the aphid alarm pheromone they release when under attack by insect predators and parasitoids – resulting in the potential for greater predation (Awmack et al. 1997).

7.4 CO_2 Enrichment

Direct effects of higher CO_2 concentrations on insects are basically not investigated. It seems that insects can detect CO_2 sources such as plants and elevated levels might affect the insect's CO_2-sensing system.

There is a general agreement between scientists that the reduced nutrient quality of C3 plants might lead to a compensation by increased feeding of many, but not all, herbivorous species (DeLucia et al. 2008). Under elevated CO_2, population densities of chewing insects are unaffected or decrease, but do not increase while sap sucker (phloem feeder) population densities might increase.

However, the results from experiments with aphids (phloem feeders) feeding on plants grown under elevated CO_2 and/or at elevated temperature have not shown consistent results. In some cases, aphid performance was not (significantly) influenced by either elevated temperature or elevated CO_2 (Diaz et al. 1998); in one research trial, two species responded very differently under same conditions (e.g., *Brevicoryne brassicae* vs. *Myzus persicae* on *Brassica napus* ssp. *oleifera*). Increased aphid infestation and reduced infestation in response to elevated CO_2 have been observed. Experiments by Awmack and Harrington (2000) showed significant effects through aphids on the peas (shoot, root weight, flower number) at elevated CO_2, although the aphid density was unaffected.

A meta-analysis of studies on elevated temperature and elevated CO_2 suggests that insect herbivore performance is adversely affected by elevated CO_2, favored by elevated temperature, and not modified when both parameters (temperature and CO_2 combined) were elevated.

It seems that current knowledge does not allow a generalization regarding the impact of climate change in herbivorous insects, especially not for the tropics. Even the trend of a northward shift of insects must not coercively translate into a pest problem – ecosystems are not that simple and human influence is quite strong. Basically, it would be necessary to investigate at least over three trophic levels with several generations of plants, herbivores, and predators/parasites, under elevated temperature and elevated CO_2.

Research with three generations of *H. armigera* reared on milky grains of spring wheat grown in ambient CO_2 concentrations and at 750 ppm showed again that bollworm fecundity was significantly decreased for the second and third generations under elevated CO_2 levels. While the consumption per larva and relative consumption rate significantly increased in elevated CO_2, the potential population consumption was significantly reduced by elevated CO_2 in the second and third generations. Therefore, the researcher suggests that net damage of cotton bollworm on wheat will be less under elevated atmospheric CO_2 levels because increased consumption is offset by slower development and reduced fertility (Chen et al. 2005).

In a similar experiment (larvae reared on milky wheat grain under 750 ppm CO_2), the researcher included a parasitoid wasp (*Microplitis mediator*) widely used as biocontrol agent of *H. armigera*. The researcher found no significant changes in wheat consumption by *H. armigera* population under elevated CO_2 or in the parasitic rate of *M. mediator*. The results indicate that the population relationship between *H. armigera* and *M. mediator* is unlikely to vary due to future elevated atmospheric CO_2 concentrations.

A multiple generation experiment compared consumption, growth, and performance of *H. armigera* feeding on transgenic Bt cotton versus conventional cotton grown under elevated CO_2 (750 ppm) versus ambient CO_2 (375 ppm). The results suggest that on the one hand damage caused by the cotton bollworm might be higher under elevated CO_2 conditions, regardless of the cotton variety. On the other hand, population abundance might be lower under elevated CO_2 compared to that under ambient CO_2 (Chen et al. 2007). The researcher explains both observations with nutritional changes under elevated CO_2 (compensatory feeding), but did not determine the nutrient content of the different experimental cotton groups.

An experiment by Coll and Hughes (2008) investigated the effects of elevated CO_2 on *H. armigera* and an omnivorous bug, which feeds on plants but also preys on the bollworm. Bollworm larvae feeding on elevated CO_2-grown pea plants (at 700 ppm) were significantly smaller than those grown on ambient-grown plants. The omnivorous bug required prey to complete its development and performed best on a mixed plant–prey diet, regardless of CO_2 level. The bugs performed best when fed larvae from the elevated CO_2 treatment apparently because these prey were smaller and thus easier to overcome. Taken together, results indicate that elevated CO_2 may benefit generalist predators through increased prey vulnerability, which would put pest species under higher risk of predation.

Recently, free air gas concentration enrichment (FACE) technology was used to create an atmosphere with CO_2 and O_2 concentrations similar to what climate change models predict for the middle of the twenty-first century. FACE allows for field testing of crop situations with fewer limitations than those conducted in enclosed spaces. During the early season, soybeans grown in elevated CO_2 atmosphere had 57 % more damage from insects (primarily Japanese beetle, potato leaf hopper, Western corn rootworm, and Mexican bean beetle) than those grown in today's atmosphere and required an insecticide treatment in order to continue the experiment. It is thought that measured increases in the levels of simple sugars in the soybean leaves may have stimulated the additional insect feeding (Hamilton et al. 2005).

Other researchers have observed that insects sometimes feed more on leaves that have lowered nitrogen content in order to obtain sufficient nitrogen for their metabolism (Coviella and Trumble 1999). Increased carbon to nitrogen ratios in plant tissue resulting from increased CO_2 levels may slow insect development and increase the length of life stages vulnerable to attack by parasitoids (Coviella and Trumble 1999).

7.4.1 Spider Mites

In one study, two-spotted spider mites (*Tetranychus urticae*) were raised on common beans grown at 600 and 700 ppm CO_2. A significant decrease in the number of the offspring in the first and second generations (34 and 49 %), respectively, was observed compared to ambient CO_2. A similar experiment was conducted, where *T. urticae* were raised on clover (*Trifolium repens*) grown at different CO_2 levels (395–748 ppm). The results showed a quite opposite effect: under elevated CO_2, spider mite reproduction increased significantly compared to lower CO_2. They noted that slight temperature differences could cause significantly different reproduction rates.

Effect of increased CO_2 effects on insect–plant interaction has been presented in Table 7.3.

Table 7.3 Effect of increased CO_2 effects on insect–plant interaction

Order	Herbivore species	Host species	Effects	Comments
Acarina	*Tetranychus urticae* (red spider mite)	*Trifolium repens* (white clover)	–	
		Gossypium hirsutum (upland cotton)	–	
		Phaseolus vulgaris (kidney bean)	+	
Coleopteran	*Papillio japonica* (Japanese beetle)	*Glycine max* (soybean)	–	Beetles and aphids generally perform better to the detriment of the plants
	Diabrotica virgifera (Western corn rootworm)	*Glycine max* (soybean)	–	
	Sitona lepidus (clover root weevil)	*Trifolium repens* (white clover)	–	
Diptera	*Pegomya nigritarsis* (leaf-mining fly)	*Rumex crispus* (invasive dock)	–	
		R. obtusifolius (invasive dock)	–	
	Chromatomyla syngenesiae (leaf-mining fly)	*Sonchus oleraceus* (invasive sow thistle)	+	
	Bemisia tabaci (sweet potato whitefly)	*Gossypium* (cotton)	ǿ	
Hemiptera	*Aulocorthum solani* (glasshouse potato aphid)	*Vicia faba* (broad bean)	–	Beetles and aphids generally perform better to the detriment of the plants
	Sitobion avenae (grain aphid)	*Triticum aestivum* (spring wheat)	–	
	Myzus persicae (green peach aphid)	*Poa annua* (grass)	–	
		Brassica napus (oilseed rape)	+	
	Brevicoryne brassicae (cabbage aphid)	*Brassica napus* (oilseed rape)	ǿ	
	Aphis glycines (soybean aphid)	*Glycine max* (soybean)	–	

(continued)

Table 7.3 (continued)

Order	Herbivore species	Host species	Effects	Comments
Hymenoptera	*Aphidius matricariae* (green peach aphid parasitoid)	*Poa annua* (grass)	ǿ	
Lepidoptera	*Pseudoplusia includens* (soybean looper)	*Glycine max* (soybean)	–	Caterpillars generally eat more to compensate, but enhanced plant growth results in little net effect
	Trichoplusia ni (cabbage looper)	*Phaseolus lunata* (lima bean)	ǿ	
	Spodoptera eridania (southern armyworm)	*Mentha piperita* (peppermint)	ǿ	
	Spodoptera frugiperda (fall armyworm)	*Festuca arundinacea* (tall fescue)	ǿ	
	Pectinophora gossypiella (pink bollworm)	*Gossypium hirsutum* (upland cotton)	ǿ	
	Helicoverpa armigera (cotton bollworm)	*Gossypium* (cotton)	+	

7.5 Expansion of Geographical Distribution

Climate change will have a major effect on geographic distribution of insect pests, and low temperatures are often more important than high temperatures in determining geographical distribution of insect pests (Hill 1987). Increasing temperatures may result in a greater ability to overwinter in insect species limited by low temperatures at higher latitudes, extending their geographical range (Fig. 7.3) (EPA 1989; Elphinstone and Toth 2008), and sudden outbreaks of insect pests can wipe out certain crop species and also encourage the invasion by exotic species (Kannan and James 2009). Spatial shifts in distribution of crops under changing climatic conditions will also influence the distribution of insect pests in a geographical region (Parry and Carter 1989). Some plant species may be unable to follow the climate change, resulting in extinction of species that are specific to particular hosts (Thomas et al. 2004). However, whether or not an insect pest would move with a crop into a new habitat will depend on other environmental conditions such as the presence of overwintering sites, soil type, and moisture, e.g., populations of the corn earworm, *Heliothis zea*, in North America might move to higher latitudes/altitudes, leading to greater damage in maize and other crops (EPA 1989).

A warmer climate in temperate regions may result in changes in geographical distribution, increased overwintering (i.e., more insects survive the winter), changes in population growth rates, increases in the number of generations, extension of the development season, changes in crop–pest synchrony, changes in interspecific interactions, and increased risk of invasion by migrant pests (Bale et al. 2002). In Japan, warmer climate led to the northward migration of the green stinkbug (*Nezara viridula*), a major agricultural pest damaging soybean, rice, cotton, and many other crops (Musolin 2007).

Geographical distribution of insect pests confined to tropical and subtropical regions will extend to temperate regions along with a shift in the areas of production of their host plants, while distribution and relative abundance of some insect species vulnerable to high temperatures in the temperate regions may decrease as a result of global warming. These species may find suitable alternative habitats at greater latitudes.

An increase of 1 and 3 °C in temperature will cause northward shifts in the potential distribution of the European corn borer, *Ostrinia nubilalis*, up to 1,220 km, with an additional generation in nearly all regions where it is currently known to occur (Porter et al. 1991).

Diamondback moth, *Plutella xylostella*, overwintered in Alberta in 1994 (Dosdall 1994), and if overwintering becomes common, the status of

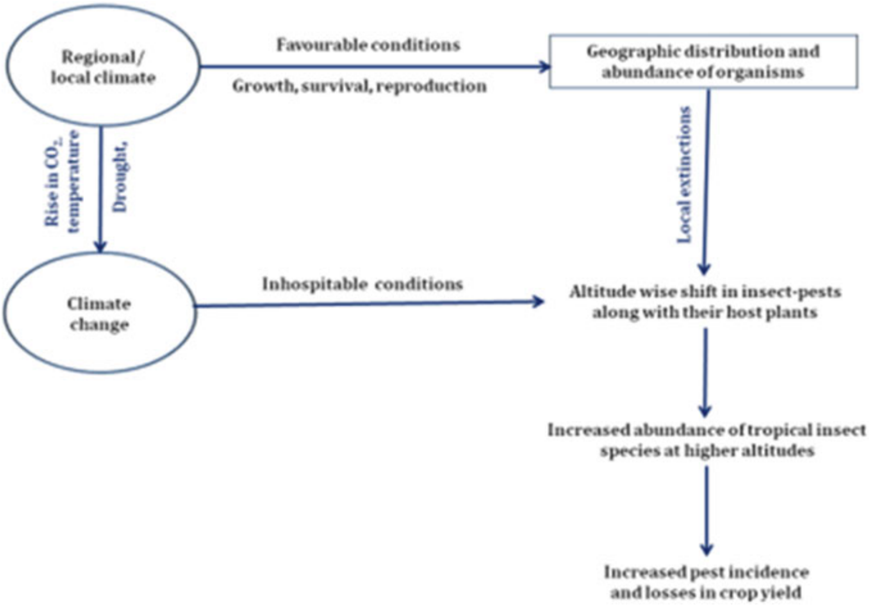

Fig. 7.3 Impact of climate change on range expansion of insect pests

this insect as a pest in North America will increase dramatically. Many insects such as *Helicoverpa* spp. are migratory and, therefore, may be well adapted to exploit new opportunities by moving rapidly into new areas as a result of climate change (Sharma et al. 2005).

Published reports of empirical studies on impact of climate change on future geographic range and distribution of insect pests are presented in Table 7.4.

Projected trends for several pests are summarized in Table 7.5. Examples of the midpoint projections of WCR infestation areas in maize are shown in Table 7.6.

Projected trends to 2020 are expected to continue up to 2050 and beyond and are useful strategic indicators for the plant breeding and crop protection industries.

7.6 Changes in Phenology

Recent climate change has led to an ecological shift in time, with changes in species' phenology. Changes in insect phenology can be studied through long-term experiments with variable sowing dates for observing the appearance of pests on crops. Likewise, the timing of arrival of insect species can also be recorded through light traps, suction traps, or pheromone traps. Analysis of long-term data on phenology would reveal changes in the timings of pest appearance under climate change.

Analysis of suction trap data at the Rothamsted Insect Survey since 1964 has revealed that spring flights of the peach potato aphid (*Myzus persicae*) started two weeks earlier for every 1 °C rise in combined mean temperature of January and February.

Likewise, long-term data from several insect-recording schemes in Europe and North America have provided evidence for species becoming active, migrating, or reproducing earlier in the year due to increases in temperatures that lead directly to increased growth rates or earlier emergence from winter inactivity (Roy and Sparks 2000). Increasing temperatures have also allowed a number of species to remain active for a longer period during the year or to increase their annual number of generations.

Under the All India Coordinated Rice Improvement Project (AICRIP) of ICAR, there is a widespread network of coordinating centers all over India that collect light trap insect data round

Table 7.4 Published reports of empirical studies on impact of climate change on future geographic range and distribution of insect pests

Insect pest	Order/family	Host plant(s)	Impact on insects/ behavioral response	References
Corn earworms, *Heliothis zea* and *Helicoverpa armigera*	Lepidoptera: Noctuidae	Maize	Altitude-wise range expansion and increased overwintering survival in the USA	Diffenbaugh et al. (2008)
European corn borer, *Ostrinia nubilalis*		Maize	Northward shifts in the potential distribution up to 1,220 km are estimated to occur	Porter et al. (1991)
			An additional generation per season	
104 common microlepidoptera species inhabitant in Netherlands	Lepidoptera	Many crops of agricultural importance	Changing patterns in phenology and distribution of microlepidoptera in the Netherlands	Kuchlein and Ellis (1997)
			Advancement of flight peak dates almost by 12 days since 1975–1194	
			Changes in the species composition of the local fauna	
Old world bollworm, *Helicoverpa armigera*	Lepidoptera: Noctuidae		Phenomenal increase in the UK from 1969 to 2004 and outbreaks at the northern edge of its range in Europe	Cannon (1998)
Cottony cushion scale, *Icerya purchasi*			Populations appear to be spreading northwards	Cannon (1998)
Oak processionary moth, *Thaumetopoea processionea*			Northward range extension from Central and Southern Europe into Belgium, the Netherlands, and Denmark	Cannon (1998)
Cottony camellia scale, *Chloropulvinaria floccifera*			More abundant in the UK	Cannon (1998)
			Extending its range northwards in England and increasing its host range in the last decade	
35 species of nonmigratory European butterflies	Papilionidae, Lycaenidae, Nymphalidae, Satyrinae		Poleward shift of the geographic range and distribution	Parmesan and Yohe (2003)
Cotton bollworm/pulse pod borer, *Helicoverpa armigera*	Lepidoptera: Noctuidae	Cotton, pulses, vegetables	Expansion of geographic range in northern India	Sharma et al. (2010)
			Adult flights/migratory behavior	

Table 7.5 Outline trends in selected pests by 2020

Species/crop	General trend	Europe	North America
Western corn rootworm in maize	Spreads with temperature rise	Extension from current outbreaks	Spreads to 50 % of crop area
European corn borer (*Ostrinia nubilalis*) in maize	More generations; spreads north	Moves with crop	More frequent outbreaks
Colorado beetle in potato	Adaptable; moves north	Could become established in the UK and Scandinavia	More frequent in Canada

Table 7.6 Estimated impact of climate change on Western corn rootworm infestations in maize

	Crop area (million ha)		Crop area infested (million ha)	
Region	2004	2020	2004	2020
Europe	15.1	18.1	<0.1	2.1
North America	30.8	32.3	12.0	19.0

the year. Analysis of historical light trap data vis-à-vis current data can provide important information on the impacts of climate change on rice pests.

7.7 Varying Precipitation Patterns

There are fewer scientific studies on the effect of precipitation on insects than temperature. Some insects are sensitive to precipitation and are killed or removed from crops by heavy rains – in some northeastern US states, this consideration is important when choosing management options for onion thrips (Reiners and Petzoldt 2005). For some insects that overwinter in soil, such as the cranberry fruit worm and other cranberry insect pests, flooding the soil has been used as a control measure. One would expect the predicted more frequent and intense precipitation events forecasted with climate change to negatively impact these insects. Other insects such as pea aphids are not tolerant of drought (Macvean and Dixon 2001). As with temperature, precipitation changes can impact insect pest predators, parasitoids, and diseases resulting in a complex dynamic. Fungal pathogens of insects are favored by high humidity, and their incidence would be increased by climate changes that lengthen periods of high humidity and reduced by those that result in drier conditions. Guiterrez et al. (2008) found that during the normally wet Northern California winter, the fungal pathogen (*Pandora neoaphidis*) causes catastrophic mortality to pea aphid (*Acyrthosiphon pisum*).

Precipitation – whether optimal, excessive, or insufficient – is a key variable that also affects crop–pest interactions. Drought stress sometimes brings increased insect pest outbreaks. It is well known that drought can change the physiology of host species, leading to changes in the insects that feed on them (Mattson and Haack 1987). Abnormally cool, wet conditions can also bring on severe insect infestations, although excessive soil moisture may drown out soil-residing insects.

Chen and McCarl (2001) investigated the relationship of precipitation and pesticide costs for several crops in the USA and concluded that increases in rainfall lead to increases in average pesticide costs for corn, cotton, potatoes, soybeans, and wheat.

Distribution and frequency of rainfall may also affect the incidence of pests directly as well as through changes in humidity levels. It is being predicted that under climate change, frequency of rainfall would decline while its intensity would increase. This would lead to heavy showers and floods on one hand and drought spells on the other. Under such situations, incidence of small pests such as aphids, jassids, whiteflies, mites, etc. on crops may be reduced as these get washed away by the heavy rains.

Armyworm, *Mythimna separata*, reaches outbreak proportions after heavy rains and floods. Lever (1969) had analyzed the relationship between outbreaks of armyworm and to a lesser extent *Spodoptera mauritia* and rainfall from 1938 to 1965 and observed that all but three outbreaks occurred when rainfall exceeded the average 89 cm. The effect of rainfall on pests can be studied by simulating various rainfall intensities through sprinklers. Aphid population on wheat and other crops was adversely affected by rainfall and sprinkler irrigation (Chander 1998).

Masters et al. (1998) have carried out novel manipulations of local climate to investigate how warmer winters with either wetter or drier summers would affect the homopteran insects – a major component of the insect fauna of grasslands. Direct and indirect effects of climate manipulation were observed. It was observed that the supplemented summer rainfall resulted in an increase in the vegetation cover, leading to an increase in the abundance of the insects. Summer drought, however, caused a decrease in the vegetation cover, but this did not lead to a

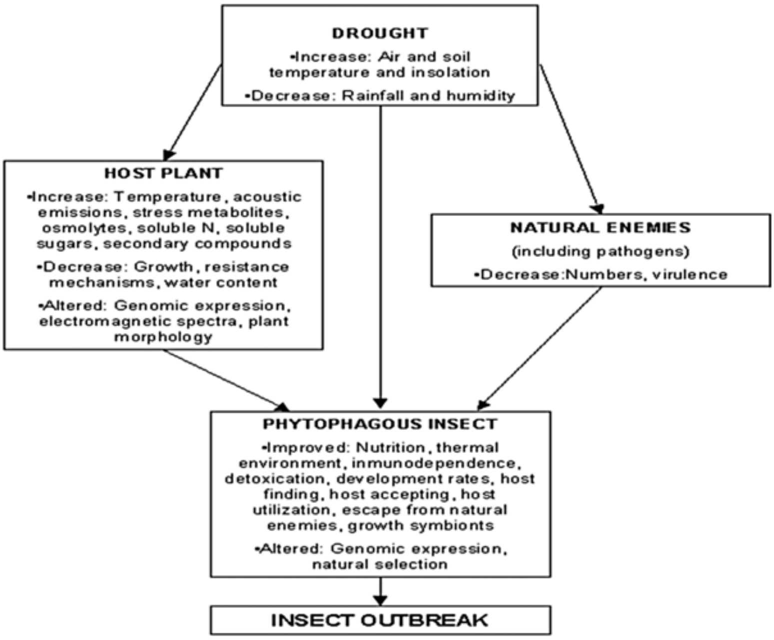

Fig. 7.4 Drought influences on host plants, phytophagous insects, and their natural enemies leading to insect outbreaks (Mattson and Haack 1987)

corresponding decrease in the abundance of the insects. Egg hatch and the termination of nymphal hibernation occurred earlier in the winter-warmed plots, but the rate of nymphal development was unaffected.

7.8 Drought

Drought stress sometimes brings increased insect pest outbreaks. It is well known that drought can change the physiology of host species, leading to changes in the insects that feed on them (Mattson and Haack 1987) (Fig. 7.4).

7.9 Increased Overwintering Survival

Theoretically, it is hypothesized that the winter survival of insects will be improved by an increase in winter temperature, but the evidence for this hypothesis is rather scarce. Effect of climate change on winter mortality/survival can be examined by collecting long-term data on winter survival at fixed overwintering sites. Relationship can then be established between winter mortality and temperature.

Kiritani (1971) had examined the winter mortality of adults of *Nezara viridula* in the late March at fixed overwintering sites from 1962 to 1967 in Wakayama. A regression between winter mortality (Y) and the mean temperature in January (X) [$Y = -16.45X + 147.08$ ($R2 = 0.6127$, $P < 0.0001$)] suggested that every 1 °C rise around $X = 4$ °C would result in a decrease in winter mortality by about 16.5 %.

Being poikilotherms, insects have limited ability of homeostasis with external temperature changes. Hence, they have developed a range of strategies such as behavioral avoidance through migration and physiological adaptations like diapause to support life under thermally stressful environments (Bale and Hayward 2010). Diapause is a period of suspended developmental activities, the manifestation of which is governed by environmental factors like temperature, humidity, and photoperiod. As an adaptive trait, diapause plays vital role in seasonal regulation of insect life cycles because of which the insects

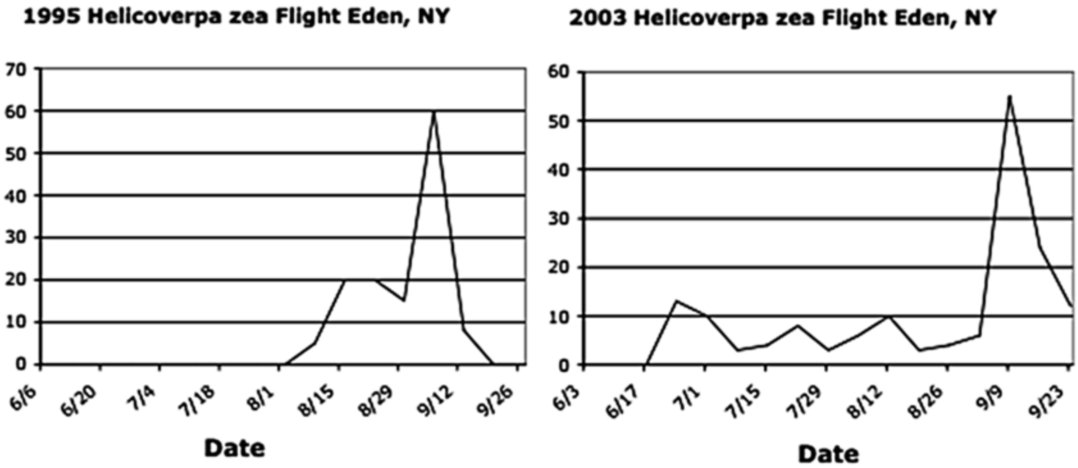

Fig. 7.5 Trap catch data indicating possible overwintering of corn earworm in western NY

have better advantage to survive great deal of environmental adversities. There are two main types of insect diapause: aestivation and hibernation to sustain life under high and low temperature extremes, respectively (Chapman 1998).

The studies have shown that global warming is occurring notably in winter than in summer and is greatest at high latitudes (IMD 2010). Looking at the past 100 years' climate profile of India, warming was more pronounced during winter season, and it was the minimum and not the maximum temperature where significant increase was observed (IMD 2010). The temperature in India is expected to increase by 1–5 °C within next 100 years (IMD 2010). Thus, insects undergoing a winter diapause are likely to experience the most significant changes in their thermal environment (Bale and Hayward 2010).

Accelerated metabolic rates at higher temperatures shorten the duration of insect diapause due to faster depletion of stored nutrient resources (Hahn and Denlinger 2007). Warming in winter may cause delay in onset, and early summer may lead to faster termination of diapause in insects, which can then resume their active growth and development. This gives an important implication that increase in temperature in the range of 1–5 °C would increase insect survival due to low winter mortality, increased population buildup, early infestations, and resultant crop damage by insect pests under global warming scenario (Harrington et al. 2001; Sharma et al. 2010). Very few studies have concentrated on the direct effects of higher winter temperatures on rates of development and reproduction in insects (Bale and Hayward 2010).

In New York, a network of pheromone traps in sweet corn fields has been used to monitor corn earworm (*Helicoverpa zea*) throughout the central and western part of the state for over 10 years. Corn earworm is thought not to overwinter in upstate New York and is generally considered to be a late season, migratory pest of sweet corn, so trapping was initiated in mid-July. The graphs in Fig. 7.5 compare the trap catches in 1995 with those in 2003 in Eden Valley, NY.

During the early years of the trap network, CEW traps remained empty until mid–late August. After an unexpected early-season infestation in Eden in 1999, trapping was initiated in early June, and typically, low levels of moths are caught through the early season, increasing when the migratory flight arrives. It is yet to be determined if the earlier arrival of corn earworm indicates it is overwintering in Eden, but since CEW management recommendations are based on trap catches, it is clear that control of this pest is already costing farmers more than it did 9 years ago.

7.10 Natural Enemies

Biological control of insect pests is one of the important components of integrated pest management, safeguarding the ecosystem. Natural enemies of crop pests, viz., predators, parasitoids, and pathogens, are prompt density responsive in their action subjected to the action of abiotic components. Being tiny and delicate, natural enemies of the insect pests are more sensitive to the climatic extremes like heat, cold, wind, and rains. Precipitation changes can also affect predators, parasitoids, and pathogens of insect pests resulting in a complex dynamics. With changing climate, incidence of entomopathogenic fungi might be favored by prolonged humidity conditions and obstinately be reduced by drier conditions (Newton et al. 2011). Natural enemy and host insect populations may respond differently to changes in climate. Hosts may pass through vulnerable life stages more quickly at higher temperatures, reducing the window of opportunity for parasitism which may give great setback to the survival and multiplication of parasitoids (Petzoldt and Seaman 2010).

Ecologists argue that the tritrophic interactions between plants, herbivorous insects, and their natural enemies (predators, parasitoids, and pathogens) result from a long coevolutionary process specific to a particular environment and relatively stable climatic conditions (Hance et al. 2007). Abrupt environmental changes as induced by current climatic change and elevated CO_2 may influence the biology of each component of a system differently, provoking a destabilization in their population dynamics that may lead to the extinction of part of the system. Specialists, for example, many host-specific parasitoids, which evolved under rather stable conditions might be especially endangered.

Atmospheric CO_2 levels may affect the performance of natural enemies and/or susceptibility of prey via a variety of indirect effects. Some of these impacts, which potentially make prey more susceptible to their enemies, include:

- Herbivores that feed on poor host plants under elevated CO_2 conditions often spend more time in the more vulnerable, early stages of development and thus may suffer greater mortality from natural enemies.
- Herbivores may be physically weakened while feeding on poor hosts under elevated CO_2 conditions and are thus less able to defend themselves against predators and parasitoids; and enriched CO_2 may alter enemy-avoidance behavior; some aphids, for example, show reduced responses to alarm pheromones under elevated CO_2, potentially making them more susceptible to enemy attack (Awmack et al. 1997).

Such effects would increase the susceptibility of herbivores to natural enemies, reducing herbivore population size under elevated CO_2 conditions (Coll and Hughes 2008).

Elevated temperature basically favors adult hunting insects and spiders, and it seems that the lethal temperature of many spiders is much above the temperature expected by climate change. Skirvin et al. (1997) modeled the interaction of ladybird (*Coccinella septempunctata*) with aphid populations (*Sitobion avenae*) and predict that in hot summer coccinellids reduce aphids more strongly than in moderate summers.

7.10.1 Pathogens

Fungi, bacteria, microsporidia, and viruses can successfully affect rodents, insect pests, and mites. They are widely used in biological control, with the bacteria *Bacillus thuringiensis* and the fungi *Beauveria bassiana* being prominent examples.

Effects of climate change on the efficiency of pathogens depend on the environment they live in. In general, fungi and bacteria benefit from warm and moist environments; therefore, mild and wetter winters as predicted in temperate zones will benefit them, especially those living in the soil (e.g., *Beauveria bassiana*). Since many larvae or pupae of pests also overwinter (pass through or wait out the winter season) in soils, fungi and bacteria might affect them more strongly.

Guiterrez et al. (2008) found that during the normally wet Northern California winter, the fungal pathogen (*Pandora neoaphidis*) causes catastrophic mortality to pea aphid (*Acyrthosiphon pisum*), but during hot dry periods, the impact of the pathogen declines.

Most entomopathogenic fungi have optimal growth temperatures between 25 and 35 °C. *Beauveria bassiana* grows at a wide temperature range (from 8 to 35 °C) with a maximum thermal threshold for growth at 37 °C. Higher temperatures, low humidity, as well as direct exposure to UV radiation reduce efficiency of pathogens.

However, each pathogen responds to temperatures differently and behavior of the host in response to temperature is important as well (Blanford and Thomas 1999). Manning and von Tiedemann (1995) showed that direct exposure of bacteria and fungi to high levels of CO_2 concentrations often inhibits their growth.

Some pathogens, which always live in the host body, might not be affected directly by climatic changes, they basically follow the development of their hosts. The effects of higher temperature on the impact of the microsporidia, *Nosema lymantriae*, on the gypsy moth (*Lymantria dispar*) clearly showed a much higher and earlier mortality of gypsy moth larvae at higher temperatures (Pollan 2009).

Pathogens, especially viruses, become more deadly if the vector/host is weakened; therefore, environmental stress such as high or low temperature might lead to higher mortality. Considering that herbivorous pests are potentially weakened by the lower nutritional quality of (C3) plants grown under elevated CO_2, it could be assumed that mortality of pests feeding on C3 crops increases when infected with pathogens (with potentially serious consequences also for some natural ecosystems). However, it seems that no one has investigated this kind of interactions so far.

7.10.2 Parasitoids

Parasitoids which live on crop pests belong to the third trophic level. Thus, they are indirectly or directly affected by any changes of the first (plant) and second level (herbivore). It is not at all clear what happens to herbivores under climate change; therefore, conclusions for parasitoids are speculative. However, there are some ecological "laws" which imply certain scenarios. If a herbivore reproduces less, because of low nutritional value, less potential hosts are available for the parasitoid. If the host changes its seasonal appearance or behavior due to climatic changes, the parasitoid might not be able to locate the host. Finally, parasitoids might be adversely affected, if the host dies too early due to additional environmental stress. However, in temperate zones, milder winters might enhance survival of parasitoids. Legrand et al. (2004) have shown that parasitoids of cereal aphids are active in winter and this winter activity can considerably reduce spring aphid populations.

No experiments have been conducted to investigate changes of all three trophic levels together (plant–herbivore–parasitoid) under climate change (elevated CO_2 and temperature). Bezemer et al. (1998) conducted an experiment involving several plant species, aphids, and parasitoids under elevated CO_2 (+200 ppm of ambient concentrations) and showed that elevated CO_2 did not influence parasitism. Elevated temperature (+2 °C of ambient temperature) increased parasitism by about 300 % on average, but due to high variation between the replicates, no significance could be detected.

A mathematical model has been developed that predicts responses of grasses, cereal aphids, and parasitoids to combined effects of elevated CO_2 and elevated temperature. Their results suggest that aphid and parasitoid populations will develop more similar to current ambient conditions than expected from the individual effects of CO_2 or temperature increases.

In one experiment with cotton bollworm, larvae reared on milky wheat grain under 750 ppm CO_2, researchers included a parasitoid wasp (*Microplitis mediator*) widely used as biocontrol agent of the cotton bollworm (*Helicoverpa armigera*). The researchers found no significant changes in wheat consumption by *H. armigera* population under elevated CO_2 or in the parasitic rate of *M. mediator*. The researchers concluded that the population relationship between *H. armigera* and *M. mediator* is unlikely to vary due to future elevated atmospheric CO_2 concentrations.

The development of a parasitoid wasp (*Glyptapanteles liparidis*) of gypsy moth (*Lymantria dispar*) feeding on three different tree species fumigated with 540 ± 20 ppm CO_2 was not adversely affected by changes in food quality when compared to ambient CO_2. However, it must be taken into account that the effects of elevated CO_2 on mature trees might not be comparable to annual plants or tree seedlings.

The precipitation variability seems to be a key factor influencing parasitism in 15 Lepidoptera (butterfly) rearing programs from a broad spectrum of climatic regimes and locations, from the region between southern Canada and central Brazil. A higher variability led to a decrease in parasitism. These findings basically support the theory that interaction, which evolved due to stable conditions, is weakened when frequent changes occur.

In general, host-specific parasitoids should be more sensitive to variations in host emergence time or developmental rate when compared to generalists. Specialist parasitoids may miss narrow windows of vulnerability of their particular hosts. In contrast, because generalists exploit a variety of hosts that might individually respond to climatic cues in different ways, they should be less susceptible to the host population's lags and asynchronies associated with climatic unpredictability.

7.10.3 Predators

Like parasitoids, predators which prey on crop pests belong to the third trophic level. Thus, they are indirectly or directly affected by any changes of the first (plant) and second level (herbivore).

7.11 Breakdown of Host Plant Resistance

Host plant resistance is one of the eco-friendly options for managing harmful insect pests of crops wherein the plant can lessen the damage caused by insect pests through various mechanisms like antixenosis, antibiosis, and tolerance (Dhaliwal and Dilawari 1993). However, expression of the host plant resistance is greatly influenced by environmental factors like temperature, sunlight, soil moisture, air pollution, etc. Under stressful environment, plant becomes more susceptible to attack by insect pests because of weakening of their own defensive system resulting in pest outbreaks and more crop damage (Rhoades 1985). Thermal and drought stress-associated breakdown of plant resistance has been widely reported (Rhoades 1985; Sharma et al. 2005). With global temperature rise and increased water stress, tropical countries like India may face the problem of severe yield loss in sorghum due to breakdown of resistance against midge *Stenodiplosis sorghicola* and spotted stem borer *Chilo partellus* (Sharma et al. 2005). Development of insect-resistant transgenics opened new avenues for exploiting host plant resistance in integrated pest management. A gene encoding delta-endotoxin proteins from entomopathogenic soil bacterium *Bacillus thuringiensis* is deployed in transgenic plants (Kranti et al. 2005). However, expression of Bt toxins in transgenic plants is greatly influenced by environmental factors like temperature, soil moisture, and plant age (Dhaliwal and Dilawari 1993; Kranti et al. 2005). The environmental factors like high temperature have been found affecting transgene expression in Bt cotton resulting in reduced production of Bt toxins. This leads to enhanced susceptibility of the crops to insect pests like bollworms, viz., *Heliothis virescens* (Kaiser 1996), *Helicoverpa armigera*, and *H. punctigera* (Hilder and Boulter 1999).

European large raspberry aphid (*Amphorophora idaei*) is the most significant insect pest of raspberry production. Aphids are vectors of at least four plant viruses that reduce plant vigor and can cause death. Two resistance genes have been introduced to overcome the aphid damage. But the aphids have partially overcome the resistance induced by the above two genes.

Global warming may result in breakdown of resistance to certain insect pests. Sorghum varieties exhibiting resistance to sorghum midge, *Stenodiplosis sorghicola*, in India become susceptible to this pest under high humidity and moderate temperatures near the Equator in Kenya. There will be increased impact on insect pests which benefit from reduced host defenses as a result of the stress caused by the lack of adaptation to suboptimal climatic conditions.

7.12 Pest Population Dynamics and Outbreaks

Climate change resultant abiotic environment (increased temperature, elevated CO_2, and depleted soil moisture) will affect significantly the diversity and abundance of insect pests through geographic range expansion, increased overwintering survival, and more number of generations per year, thereby increasing the extent of crop losses. It may result in upsetting ecological balance because of unpredictable changes in the population of insect pests along with their existing and potential natural enemies.

Changes in climatic variables have led to increased frequency and intensity of outbreaks of insect pests. Outbreak of sugarcane woolly aphid, *Ceratovacuna lanigera*, in sugarcane belt of Karnataka and Maharashtra states during 2002–2003 resulted in 30 % yield losses. These situations of increased and frequent pest damage to the crops have made another big hole in the pockets of already distressed farmers by increasing the cost of plant protection and reducing the margin of profit (Table 7.7).

7.13 Crop–Pest Interactions

The increasing temperature and CO_2 have been found to exert both bottom-up and top-down effects on the tritrophic interactions between crops, insects, and natural enemies by means of certain physiological changes especially related to host suitability and nutritional status (Table 7.8) (Roth and Lindroth 1995; Coviella and Trumble 1999; Gutierrez et al. 2008). The CO_2-enriched environment reduces the nitrogen content of the plant tissue due to widening of carbon–nitrogen (C:N) ratio, thus causing a slight decrease in nitrogen-based defenses like alkaloids and in turn may increase in carbon-based defenses such as tannins (Roth and Lindroth 1995; Coviella and Trumble 1999; Gutierrez et al. 2008). This enhances the feeding by insect herbivores in order to obtain sufficient nitrogen for their metabolism (Coviella and Trumble 1999). Ultimately, it slows down insect development and increases the length of life stages resulting in more foliage feeding than normal (Coviella and Trumble 1999).

In CO_2-enriched atmosphere, water use efficiency of plants increases owing to the reduced water loss through less stomatal opening (Groninger et al. 1996). Increased water content in plants is beneficial for most of the herbivorous insects as it helps in nutrient assimilation and digestion especially nitrogen (Reitz et al. 1997). Increased water use efficiency enables the plants to extend their life spans providing longer periods of habitat suitability for transient insects. On the contrary, under elevated temperature, the concentrations of certain allellochemicals like terpenes and phenolic compounds increase in plants that act as defensives against the attacking insect pests (Roth and Lindroth 1995; Coviella and Trumble 1999; Gutierrez et al. 2008).

Temperature and photoperiod have been found to affect profoundly the critical events such as stem elongation, flowering, and fruiting in the life cycle of plants (Cleland et al. 2007). Global warming that leads to increased temperatures may accelerate the life cycles in some of the plant species (Parmesan and Yohe 2003; Willis et al. 2008) which may affect, significantly, feeding and reproduction patterns in associated insect pests like aphids, jassids, mealy bugs, etc. Such increases can greatly exacerbate the negative ecological and economical consequences (Timoney 2003).

7.14 Disruption of Plant–Pollinator Interactions

Insects play a vital role in providing various ecosystem services, a foundation for human life on earth (Kannan and James 2009). One of the important ecosystem services provided by insects is pollination

Table 7.7 Recorded instances of recent insect pest outbreaks in relation to changing climate scenario in India

Insect pest	Order/family	Host plant/s	Region/ location	Probable reason(s)	Impact of pest outbreak	References
Sugarcane woolly aphid, *Ceratovacuna lanigera*	Hemiptera: Aphididae	Sugarcane	Sugarcane belt of Karnataka and Maharashtra States during 2002–2003	Recent abnormal weather patterns	30 % yield losses	Srikanth (2007)
				Insecticide misuse	Reduced cane recovery	
Rice plant hoppers, *Nilaparvata lugens* and *Sogatella furcifera*	Hemiptera: Fulgoridae	Rice	North India	Recent abnormal weather patterns	Crop failure over more than 33,000 ha paddy area	IARI News (2008)
				Insecticide misuse		
Mealybug, *Phenacoccus solenopsis*	Hemiptera: Pseudococcidae	Cotton, vegetables, ornamentals	Cotton growing belt of the country	Recent abnormal weather patterns	Heavy yield (30–40 %) loss of cotton	Dhawan et al. (2007)
				Insecticide misuse	Increased cost of crop protection due to overuse of pesticides	
				Changed cropping environment (introduction of Bt cotton)		
Papaya mealybug, *Paracoccus marginatus*	Hemiptera: Pseudococcidae	Papaya	Tamil Nadu, Karnataka, Maharashtra	Recent abnormal weather patterns	Significant yield loss to the papaya growers	Tanwar et al. (2010)
				Insecticide misuse		

Table 7.8 Published reports on empirical studies on crop–insect pest interactions in the context of climate change

Insect pest	Order/family	Host plant(s)	Climatic factor(s) studied	Impact on host plant	Impact on insect pest	References
Many foliage feeding Lepidopterans	Lepidoptera: Lymantriidae, Noctuidae, Pyralidae	Economically important agricultural and forest species	Increased CO_2	Reduced nitrogen content of the plant tissue due to widening of C/N ratio	Enhanced feeding by insects in order to obtain sufficient nitrogen for their metabolism	Coviella and Trumble (1999)
				Decrease in nitrogen-based plant defenses like alkaloids	Slower development	
				Increase in carbon-based defenses such as tannins	Increased length of life stages	
					More foliage feeding than normal	
				Less stomatal opening	Extension of plant life spans	Reitz et al. (1997)
				Increased water use efficiency	Ease in nutrient assimilation and digestion especially the nitrogen	
				Reduced water loss through stomata	Longer periods of habitat suitability for insects	
Gypsy moth, *Lymantria dispar*	Lepidoptera: Noctuidae	Red maple, (*Acer rubrum*), sugar maple, (*Acer saccharum*)	Temperature x CO_2 combination (ambient and elevated)	Reduced leaf water content	Reduced larval weight gain	Williams et al. (2000)
				Increased concentration of soluble sugars	Increased larval feeding	
				Declined nutritional quality of foliage	Prolonged development	
Midge (*Stenodiplosis sorghicola*) and spotted stem borer (*Chilo partellus*)	Diptera: Cecidomyiidae	Jowar, *Sorghum bicolor*	High temperature, drought/water stress	Breakdown of resistance against target insect pests	–	Sharma et al. (2005, 2010)
	Lepidoptera: Pyralidae			Heavy loss in yield due to increased pest damage		
Bollworms, *Heliothis virescens, Helicoverpa armigera*, and *H. punctigera*	Lepidoptera: Noctuidae	Cotton	High temperature, drought/water stress, photoperiod	Negative impacts on transgene expression in Bt cotton	–	Kaiser (1996), Hilder and Boulter (1999)
				Reduced production of Bt toxins		
				Enhanced susceptibility of crops to insect pests		

as they are excellent pollinators for many of the economically important crops (Sidhu and Mehta 2008). The majority of the flowering plants require insect pollinators like flies, butterflies, moths, beetles, and especially bees for their reproduction and formation of fruits and seeds (Ricketts et al. 2008). Honey bees are perhaps the best known pollinators because of their floral fidelity. Insect pollination, mostly by bees, is necessary for 75 % of all crops that are used directly for human food worldwide. Thus, the entomophilies pollination is a fundamental process essential for the production of about one-third of the world human food (Klein et al. 2007).

According to Millennium Ecosystem Assessment Report 2005, pollination is one of the 15 major ecosystem services currently under threat from mounting pressures exerted by growing population, depleting natural resource base and global climate change (Sachs 2008). Earlier studies have clearly shown that the population abundance, geographic range, and pollination activities of important pollinator species like bees, moths, and butterflies are declining considerably with changing climate (FAO 2008). The climatic factors like temperature and water availability have been found to affect profoundly the critical events like flowering, pollination, and fruiting in the life cycle of plants (Cleland et al. 2007). Many pollinators have synchronized their life cycles with plant phenological events. Impending climate change is expected to disrupt the synchrony between plant–pollinator relationships by changing the phenological events in their life cycles and may thus affect the extent of pollination (Ricketts et al. 2008). The quality and the quantity of pollination have multiple implications for food security, species diversity, ecosystem stability, and resilience to climate change (FAO 2008).

Although pollination is a critical issue, it appears to be neglected and overlooked for other ecosystem services such as water and air quality, climate regulation, and food availability. The pollination services and associated risks are not addressed properly in determining the actions needed for conserving pollinators. The high degree of uncertainty regarding the risks related to pollination services implies the need for well-focused research to understand scientifically the pollination processes.

7.15 Food Security

The greatest challenge for humanity in the coming century is to double the present levels of food production to meet the needs of an ever-increasing population by sustainable use of shrinking natural resource base (Deka et al. 2008). The aggravating pest problems under changing climate regimes are expected to intensify yield losses, threatening the food security of the countries with high dependency on agriculture (Chahal et al. 2008). Climate change is likely to affect the extent of entomophilous pollination by disrupting the synchrony between plant–pollinator life cycles (Kudo et al. 2004), with an estimated risk of reduction in world food production by one-third (Klein et al. 2007). This has major implication for food and nutritional security (FAO 2008). This may have direct bearing on the livelihood of the rural poor as their survival is directly linked to outcomes from food production systems. The increased food prices resulting from declining food production may also impact negatively the urban population (Chahal et al. 2008).

Some of the strategies that are useful in tackling the issue are pointed out below:

- Sensitization of stakeholders about climate change and its impacts
- Farmers' participatory research for enhancing adaptive capacity
- Promotion of resource conservation technologies
  - Breeding climate-resilient varieties
  - Rescheduling of crop calendars
  - GIS-based risk mapping of crop pests
  - Screening of pesticides with novel mode of actions

7.16 Reduced Effectiveness of Pest Management Strategies

Certain effective cultural pest management practices like crop rotation, early/late planting, etc. will be less or not effective with changed climate because of shrinking of crop growing seasons, colonization of crops by early insect arrival, and/

or increased winter survival (Harrington et al. 2001; Sharma et al. 2005; Petzoldt and Seaman 2010). Disruption of synchrony between insect pests and their natural enemies may upset the natural biological control (Petzoldt and Seaman 2010). Certain pesticides like pyrethroids and organophosphates and especially the biopesticides being highly thermo-unstable degrade faster at higher temperatures. Altered temperature regimes may render many of these products to be less or not effective in pest control, necessitating frequent insecticide applications for effective control (Musser and Shelton 2005). This may intensify the pest problems due to the increased chances of resistance development in insects. Ultimately it will add to increased cost of crop protection to the farmers and in turn environmental cost (Musser and Shelton 2005; Petzoldt and Seaman 2010). The forewarning models for predicting insect arrival/infestations based on earlier climate profiles need to be revised in accordance with location-specific changes in climate in order to provide precise and accurate forecast of pest incidence.

A number of cultural practices that can be used by farmers could be affected by changes in climate – although it is not clear whether these practices would be helped, hindered, or not affected by the anticipated changes. Using crop rotation as an insect management strategy could be less effective with earlier insect arrival or increased overwintering of insects. However, this could be balanced by changes in the earliness of crop planting times, development, and harvest. Row covers used for insect exclusion might have to be removed earlier to prevent crop damage by excessive temperatures under the covers – would the targeted early insects also complete their damaging periods earlier or be ready to attack when the row covers were removed?

7.17 Increased Pesticide Usage

It is likely that farmers will experience extensive impacts on insect management strategies with changes in climate. Entomologists expect that insects will expand their geographic ranges and increase reproduction rates and overwintering success. This means that it is likely that farmers in the northeastern USA will have more types and higher numbers of insects to manage. Based on current comparisons of insecticide usage between more southern states and more northern states, this is likely to mean more insecticide use and expense for northeastern farmers. New York conditions currently require 0–5 insecticide applications against lepidopteron insect pests to produce marketable sweet corn (Stivers 1999); Maryland and Delaware conditions require 4–8 insecticide applications (Whitney et al. 2000); Florida conditions require 15–32 applications (Aerts et al. 1999). It is apparent that for sweet corn pests, warmer temperatures translate to increased insecticide applications to produce a marketable crop. Insecticides and their applications have significant economic costs for growers and environmental costs for society. Additionally, some classes of pesticides (pyrethroids and spinosad) have been shown to be less effective in controlling insects at higher temperatures (Musser and Shelton 2005).

Entomologists predict additional generations of important pest insects in temperate climates as a result of increased temperatures, probably necessitating more insecticide applications to maintain populations below economic damage thresholds. A basic rule of thumb for avoiding the development of insecticide resistance is to apply insecticides with a particular mode of action less frequently (Shelton et al. 2001). With more insecticide applications required, the probability of applying a given mode of action insecticide more times in a season will increase, thus increasing the probability of insects developing resistance to insecticides.

Tilman et al. (2001) foresee a 2.4–2.7-fold increase in pesticide use by 2050 related to population growth and conversion of natural ecosystems to agriculture, but the effect of climate change is not considered by the authors. Chen and McCarl (2001) investigated the relationship of temperature, precipitation, and pesticide costs for several crops in the USA and concluded that increases in rainfall lead to increases in average pesticide costs for corn, cotton, potatoes, soybeans, and wheat, while hotter weather increases pesticide costs for corn, cotton, potatoes, and soybeans but decreases the cost for wheat. A simulation by the same authors applying different climate change scenarios showed uniform increases in average pesticide costs for corn, soybeans, cotton, and potatoes and mixed results for wheat.

7.18 Modeling Approaches

Impact of climate change would depend upon on complex interactions of climatic and biological factors with technological and socioeconomic changes that are difficult to predict. Therefore, these interactions are not amenable to qualitative analyses. Hence, quantitative (modeling) approaches, which allow investigating multiple scenarios and interactions simultaneously, will become more important for the impact assessment (Coakley and Scherm 1996). Sutherst et al. (1996) have given a framework for such model-based assessment of impacts of climate change. Some of these approaches are discussed here.

7.18.1 InfoCrop Models

InfoCrop-maize, coupled with holometabolous population dynamics model, was used to simulate population dynamics of maize stem borer, *Chilo partellus*, as well as crop–pest interactions. Maize stem borer acts as a stand reducer and causes loss of leaf area, leaf weight, stem weight, and panicle weight to the crop. Larva being the damaging stage of the pest, larval population from population dynamics model was linked to the processes of leaf area, leaf weight, stem weight, and ear weight in the crop model. Depending upon larval population and feeding rate of a larva, these crop growth processes were affected. The coupled model was calibrated and validated with field experimental data on larval population and the corresponding maize yield. Validated model was used to simulate effect of 0.5–3.0 °C rise in both maximum and minimum temperatures compared to the ambient conditions on pest dynamics as well as crop–pest interactions. Simulation of pest dynamics showed a decline in the pest severity thereby reducing the pest-induced yield losses under global warming. However, maize productivity also depicted reduction even without pest stress under climate change, indicating that despite reduction in pest stress, crop productivity as such may be adversely affected by global warming.

Climate change impact assessment through coupled rice brown plant hopper (BPH) InfoCrop model, in the light of the projected climate change scenario for Indian subcontinent, showed a decline in BPH population of 3.5 % by 2020 and of 9.8–14.0 % by 2050, during the rainy season at New Delhi, while the pest population exhibited only a small decline of 2.1–3.5 % during winter at Aduthurai, Tamil Nadu, even by 2050. Simulation attributed the decline in BPH population to reduction in fecundity and survival. Concomitant to its population decline, the BPH-induced yield loss also indicated a declining trend with temperature rise. However, the study considered the effect of only CO_2 and temperature rise on the BPH population and crop yield and not that of probable changes in the feeding rate and adaptive capacity of the pest.

The impact of climate change on pink borer, *Sesamia inferens*, population, and crop–pest interaction was analyzed through coupled InfoCrop model. A rise of 0.5–1.0 °C temperature showed a small effect on various pest developmental stages, but a further increase had a significant adverse effect on them. In accordance with climate change projections for Indian subcontinent during kharif season, the study indicated that the population of *S. inferens* might decline to the extent of 5.82–22.8 % by 2020 and 19.01–42.74 % by 2050. Following decline in pest population, yield loss due to *S. inferens* also revealed a declining trend with temperature rise.

7.18.2 Climate Matching

Climate matching involves the calculation of a “match index” to quantify similarity in the climate between two or more locations. The match index is based on variables such as monthly minimum and maximum temperatures, precipitation, and evaporation rates. Software packages for climate matching include BIOCLIM122 Climate Change Impact, Adaptation, and Mitigation in Agriculture (Busby 1991), CLIMEX (Sutherst and Maywald 1985), HABITAT (Walker and Cocks 1991), and WORLD. Climate matching may be used for climate change impact assessment by identifying those locations on the globe with a current climate that is similar to the predicted future climate at the location of interest. An analysis of the plant disease problems at the matching locations based on disease distribution maps made it possible to predict the future disease risk at the location of interest.

CLIMEX software can be used to generate distribution maps of insect species and to assess the possible distributions of these insects in changing climate (Sutherst and Maywald 1985). It holds the weather data for monthly long-term average maximum and minimum temperatures, rainfall, and relative humidity from 2031 meteorological stations worldwide from 1931 to 1960. Additional weather data can be added into CLIMEX meteorological database from different meteorological stations.

CLIMEX can predict species potential distribution through weather parameters of its current habitat range or directly by the species biological parameters such as minimum, maximum, and optimum temperatures for development. On the basis of biological parameters of the species, CLIMEX generates a map for the potential geographical distribution of the species by counting an ecoclimatic index (EI). EI is a numerical value for climatic suitability and relative abundance of the species. CLIMEX calculates EI from an annual growth index, describing conditions favorable for population growth together with stress factors that limit population growth during unfavorable season in the following manner: $EI = [100/52\ (TIw \times MIw \times DIw)] \times [(1 - CS/100)\ (1 - HS/100)\ (1 - DS/100)\ (1 - WS/100)]\ \Sigma\ 52\ W = 1$ where TIw is the growth index counts for weekly temperature index, MIw is the moisture index, DIw is the diapause index, and w is the week of the year. Each of the stress indices is calculated on weekly basis and expressed as a sum over the year as annual heat (HS), cold (CS), wet (WS), and dry stress (DS) indices, all indicative of the climatic requirements of the species.

The temperature index consists of the lower temperature threshold (DV0), the lower and upper optimum temperatures (DV1 and DV2), and the upper temperature threshold (DV3). Further, the number of degree days (PDD) required to complete a generation cycle is also used. Four parameters are used in the calculations of the moisture index (MI); these are lower and upper soil moisture thresholds (SM0 and SM3) and the lower (SM1) and upper (SM2) bounds of optimum range. Diapause index is composed of diapause induction day length (DPD0), diapause induction temperature (DPT0), diapause termination temperature (DPT1), and diapause development days (DPD). The stress indices used are heat stress (HS), dry stress (DR), and wet stress (WS).

The ecoclimatic index (EI) values range from 0 to 100, describing climatic suitability of the location for the species. At the EI value of 0, the species cannot establish a viable population at the location. Values over 20 indicate a very favorable climate for the species.

CLIMEX modeling software has been used to predict the future distribution ranges of two central European serious forest pest species, the nun moth (*Lymantria monacha*) and the gypsy moth (*L. dispar*).

7.18.3 Empirical Models

Empirical models based on long-term data on pest incidence and weather variables can be used to assess the likely impact of climate change on pest status in a region.

Chander et al. (2003) have related the aphid incidence on barley crop variety "DL-70" during rabi season from 1985–1986 to 1999–2000 to weather parameters. There was appreciable interannual variation in the aphid incidence on barley, perhaps due to interannual climatic variability. The aphid population on barley exhibited a declining trend with time. The aphid population showed a negative relationship with the January mean minimum temperature ($r = -0.37$, Fig. 7.6), while it was not related to the February mean minimum temperature. The February total rainfall and aphid population

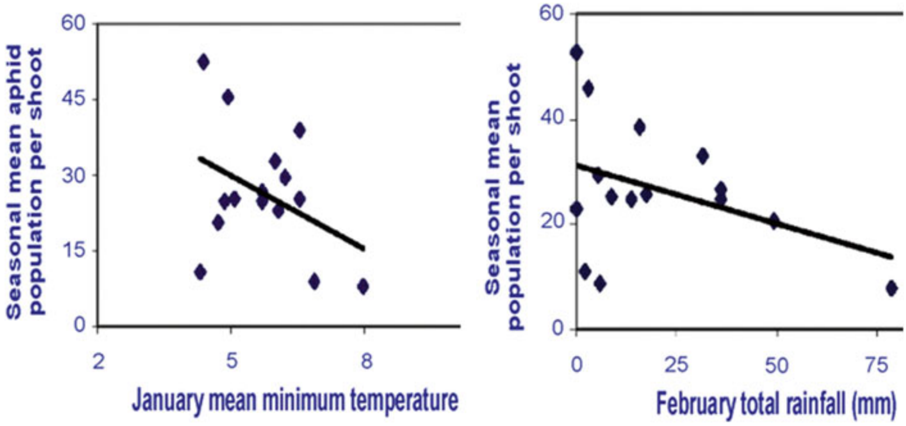

Fig. 7.6 Effect of minimum temperature and rainfall on incidence of barley aphids

were also found to be negatively related ($r = -0.27$, Fig. 7.6). Therefore, the rise in minimum temperature and more intense rains in the future as speculated might reduce aphid incidence on barley.

7.18.4 Simulation Models

Simulation models have been used widely to assess the impact of climate change on yield of various crops in different agroecological zones.

7.18.4.1 Simulation of Population Dynamics

Insect population dynamics model can be devised based on various bioecological factors, viz., fecundity, sex ratio, migration, abiotic and biotic mortality factors, threshold of development, and thermal constant. Chander et al. (2009) have developed such a model for rice gundhi bug, *Leptocorisa acuta*, which is comprised of state, rate, driving, and auxiliary variables (Fig. 7.7). State and rate variable approach was followed in developing the model. Insect population converted from one stage to another in proportion to the ratio of effective temperature to thermal constant of that stage and stage-specific mortality. Depending upon the rate of population change, total insect number in each developmental stage was updated daily.

The model was used to simulate the impact of global warming on the rice bug by altering daily minimum and maximum temperatures. It could be concluded that up to 1 °C rise in daily average temperature over the present temperature of Delhi would not affect the gundhi bug population much, but further increase would cause appreciable decline in its population.

7.18.4.2 Coupling of Population Dynamics Model to Crop Growth Simulation Model

The population dynamics model can be coupled to crop growth model at the appropriate level of plant processes, depending on the pest damage mechanisms. The damaging pest stage affects plant growth and yield based on its number and feeding rate of individuals. Crop pest model can then be used to analyze the impact of climate change on crop productivity, insect dynamics, as well as crop–pest interactions.

7.19 Adaptation

Adaptation refers to an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects that moderate, harm, or exploit beneficial opportunities.

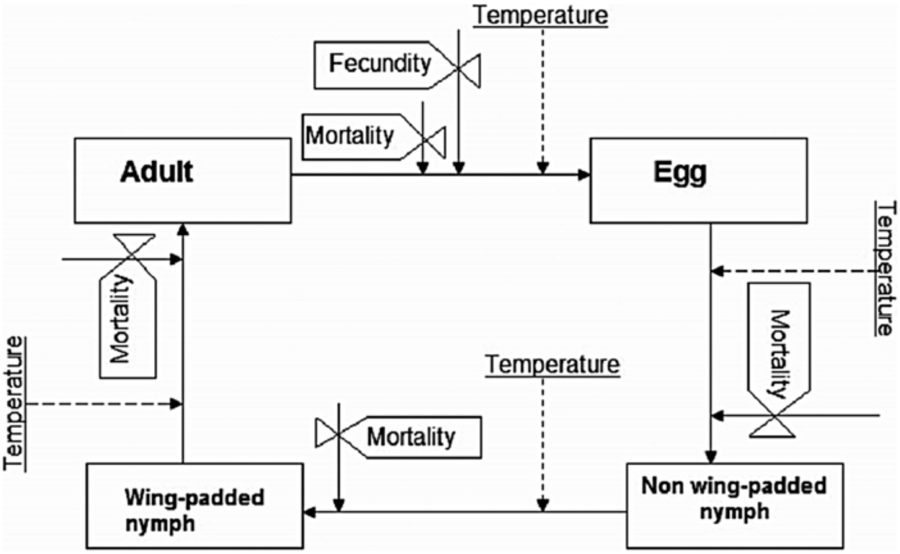

Fig. 7.7 Relational diagram showing the variables of population dynamics simulation model of rice gundhi bug

7.19.1 Promotion of Resource Conservation Technologies

Shrinking resource base due to anthropogenic developmental activities is a major challenge ahead for humanity. Conservation of natural resources can be promoted by giving incentives to the farmers who are adopting environmental conserving pest management activities such as organic farming, biocontrol, integrated pest management, habitat conservation for important insect pollinators, etc. Strategies for adaptation and coping could benefit from combining scientific and indigenous technical knowledge (ITK), especially in developing countries where technology is least developed. ITK is helpful to adapt the adverse effects of changing climate, e.g., application of natural mulches helps in suppression of harmful pests and diseases besides moderating soil temperatures and conservation of soil moisture. Furthermore, study towards integrating indigenous adaptation measures in global adaptation strategies and scientific research is required.

7.19.2 Observation of Fields and Orchards

Farmer Field School (FFS) should be started, where farmers can learn more about pests and their enemies and their management. Thorough knowledge of the pest life cycle, the ecological and behavioral interactions with the environment, and natural management factors is the basic foundation for successful management strategies (Conlong and Rutherford 2009).

7.19.3 Increased Biodiversity

Natural pest control by the natural enemies comes for free. A diverse fauna of enemy species can successfully suppress pests (Cardinale et al. 2003). The sentence can be split into two as follows: Intercropping can attract natural enemies (pull) and repel pests (push) (Cook et al. 2007). Partial weediness (as long as weeds are not host to pathogens or problematic pests), mulching, and reduced tillage increases spider abundance.

Spraying pesticides to control weeds and pests usually kills natural enemies and/or destroys their homes. As a consequence, an increase in the pest population may occur (resurgence) and need to spray more frequently, and resistant pests might emerge.

7.19.4 Avoidance of Depending on One "High Input Variety" or One Breed of Crop Variety

Breeds should be mixed and changed. A broad genetic variability serves as a foundation for robust crops. In addition, it seems more recent traditional breeding has not selected for CO_2 responsiveness, which simply means newer breeds do not benefit from elevated CO_2 as much as older breeds (Ainsworth et al. 2008).

7.19.5 Following Crop Rotation to Increase Biodiversity

A return to crop rotations would substantially reduce soil erosion and water runoff and improve the control of insects. They are sound agricultural practices that should be widely used in agriculture. Noxious pests establish slower because specific relationships between pests and host plants are interrupted (Dhawan and Peshin 2009).

7.19.6 Following Ecologically Based Pest Management

Ecologically based pest management (EBPM) considers belowground and aboveground habitat management equally important. A "healthy" soil, with optimal physical, chemical, biological properties, increases plant resistance to insect and diseases (Altieri et al. 2005). Excess of nitrogen can increase the severity of certain diseases and make a crop more susceptible to pests (Altieri et al. 2005).

7.20 Mitigation

Climate change mitigation encompasses the actions being taken, and those that have been proposed, to limit the magnitude and/or rate of long-term global warming-induced climate change.

7.20.1 Breeding Climate-Resilient Varieties

In order to minimize the impacts of climate and other environmental changes, it will be crucial to breed new varieties for improved resistance to insect pests. Considering late onset and/or shorter duration of winter, there is chance of delaying and shortening the growing seasons for certain rabi/cold season crops. Hence, there is a need to concentrate on breeding varieties suitable for late planting and those that can sustain adverse climatic conditions and pest and disease incidences.

7.20.2 Rescheduling of Crop Calendars

Global temperature increase and altered rainfall patterns may result in shrinking of crop growing seasons with intense problems of early insect infestations. As such, certain effective cultural practices like crop rotation and planting dates will be less or not effective in controlling crop pests with changed climate. Hence, there is a need to change the crop calendars according to the changing crop environment. The growers of the crops have to change insect management strategies in accordance with the projected changes in pest incidence and extent of crop losses in view of the changing climate.

7.20.3 GIS-Based Risk Mapping of Crop Pests

Geographic Information System (GIS) is an enabling technology for entomologists, which help in relating insect pest outbreaks to biographic and physiographic features of the landscape and hence can best be utilized in area-wide pest management programs. How climatic changes will affect development, incidence, and population dynamics of insect pests can be studied through GIS by predicting and mapping trends of potential changes in geographical distribution (Sharma et al. 2010) and delineation of agroecological hot spots and future areas of pest risk (Yadav et al. 2010).

7.20.4 Screening of Pesticides with Novel Modes of Action

It has been reported by some researchers that the application of neonicotinoid insecticides for controlling sucking pests induces salicylic acid-associated plant defense responses which enhance plant vigor and abiotic stress tolerance, independent of their insecticidal action (Ford et al. 2010). This gives an insight into investigating the role of insecticides in enhancing stress tolerance in plants. Such compounds need to be identified for use in future crop pest management.

7.20.5 Improved Pest Control

Because insects destroy potential crop production worldwide, use of appropriate technologies to reduce pest losses would increase crop yields. In addition to the prudent application of pesticides, increased use of nonchemical pest controls would help minimize crop losses (Pimentel et al. 1993). Nonchemical controls include crop rotations, biological controls, altering planting dates and fertilizer and irrigation applications, and soil management and tillage. These technologies could help minimize projected pest losses and thereby help maintain crop yields.

7.20.6 Transgenic Crops for Pest Management

Another important issue regarding pest management in the future centers on the role of biotechnology in crop protection. The next 20 years will likely to see a substantial increase in the use of genetically engineered plants. Genetically engineered plants have been designed to resist pests such as stem borers and nematodes without the need for pesticides. Others are expected to combine both herbicide resistance and insect resistance in one seed.

Environmental factors such as soil moisture, soil fertility, and temperature have strong influence on the expression of *Bacillus thuringiensis* (Bt) toxin proteins deployed in transgenic plants (Sachs et al. 1998). Cotton bollworm, *Heliothis virescens*, destroyed Bt-transgenic cottons due to high temperatures in Texas, USA (Kaiser 1996). Similarly, *Helicoverpa armigera* and *H. punctigera* destroyed the Bt-transgenic cotton in the second half of the growing season in Australia because of reduced production of Bt toxins (Hilder and Boulter 1999). Cry1Ac levels in transgenic plants decrease with the plant age, resulting in greater susceptibility of the crop to insect pests during the later stages of crop growth (Sachs et al. 1998; Kranti et al. 2005). Possible causes for the failure of insect control in transgenic crops may be due to inadequate production of the toxin protein, effect of environment on transgene expression, Bt-resistant insect populations, and development of resistance due to inadequate management (Sharma and Ortiz 2000). It is therefore important to understand the effects of climate change on the efficacy of transgenic plants for pest management.

Colorado potato beetle (CPB) resistance in potato has been achieved through the incorporation of a gene from the *B. thuringiensis* (Bt) protein into potatoes (Russet Burbank, Atlantic).

Several developing-country potato varieties have been transformed with the Bt gene to express resistance to the potato tuber moth:

- In Central Africa (Rwanda, Burundi, Uganda, Congo), resistant varieties include Mabondo, Sangema, Murca, and Cruza.
- For the Andean region (Peru, Bolivia, Ecuador), tuber moth resistance is now in Tomasa Condemayta, Costanera, Achirana INTA, María Tambeña, and Revolución.
- In Colombia, Pardo Pastusa has been transformed.

- Costa Rica now has resistant Atzimba.
- For both North Africa (Egypt, Tunisia, Morocco) and the Southern cone of South America (Argentina, Chile), Desiree has been transformed with the Bt gene.

Desiree potato plants were genetically modified to resist attack by insect species belonging to the orders Coleoptera (Colorado potato beetle, CPB) and Lepidoptera (potato tuber moth (PTM) and European corn borer (ECB)), through the insertion of such a hybrid gene SN19 under the control of a chrysanthemum ribulose-1, 5-bisphosphate carboxylase/oxygenase small subunit (Rubisco SSU) promoter and terminator (Naimov et al. 2003). Transgenic plants were shown to be resistant against CPB larvae and adults, PTM larvae, and ECB larvae. These are the first transgenic plants resistant to pests belonging to two different insect orders.

Bt brinjal has been developed by inserting a gene cry1Ac from a soil bacterium, *B. thuringiensis*, through an *Agrobacterium*-mediated gene transfer. The Event EE1 was introgressed by plant breeding into various local varieties such as Malpur local, Manjari gota, Kudachi local, Udupi local, 112 GO, and Pabkavi local (Fig. 7.8).

Bt soybean (*Glycine max*) MON 87701 was developed by *Agrobacterium*-mediated transformation of soybean using the 2 T-DNA plasmid vector PV-GMIR9, which produces one *B. thuringiensis* subsp. *kurstaki* protein, Cry1Ac. This protein is intended to provide protection from feeding damage caused by a number of lepidopteron pests, such as the velvet bean caterpillar (*Anticarsia gemmatalis*), soybean looper (*Pseudoplusia includens*), soybean axil borer (*Epinotia aporema*), and sunflower looper (*Rachiplusia nu*) (Fig. 7.9).

Many rice varieties have been transformed with genes encoding various Bt crystal (Cry) proteins and have been shown to be resistant to one or more lepidopteron pests of rice, the most important of which are the yellow stem borer (*Scirpophaga incertulas*), the striped stem borer (*Chilo suppressalis*), and several species of leaf folders (*Marasmia* spp. and *Cnaphalocrocis medinalis*) (Pathak and Khan 1994) (Fig. 7.10).

Commercially available genetically modified crops resistant to infect pests are presented in Table 7.9 (Castle et al. 2006).

7.20.7 Integrated Pest Management

Integrated pest management (IPM) is an effective and environmentally sensitive approach to pest management that uses current, comprehensive information on the life cycles of pests and their interaction with the environment to manage pest damage by the most economical means and with the least possible hazard to people, property, and the environment.

Fig. 7.8 Damage caused by brinjal fruit and shoot borer (*left*) and Bt brinjal developed by MAHYCO (*right*)

Fig. 7.9 The nontransgenic soybean in the front shows extensive defoliation by velvetbean caterpillar, while transgenic Bt soybean in the back is healthy

Fig. 7.10 Transgenic Bt rice (MH63) showing resistance to yellow stem borer (*left*) and leaf folder (*right*). *T* transgenic, *C* control

Table 7.9 Commercially available genetically modified crops resistant to infect pests (Castle et al. 2006)

Crop	Trait phenotype	Target trait gene(s)	Trait designation	Originating company	Year of first commercial sale	Trade name
Cotton	Resistance[a] to lepidopteron	cry1Ac	MoN531	Monsanto	1996	Bollgard, Ingard
		cry1Ac, cry2Ab2	MoN15985	Monsanto	2003	Bollgard II
		cry1Fa, cry1Ac, pat	281-24-236 × 3006-210-23	Dow AgroSciences	2005	WideStrike
Corn	Resistance[a] to European corn borer and other lepidopteron insects	cry1Ab, pat	Bt11	Northrup King (now Syngenta)	1996	YieldGard Attribute
		cry1Ab	MoN810	Monsanto	1997	YieldGard (Corn Borer)
		cry1F, pat	TC1507	Dow AgroSciences; Pioneer Hi-Bred Intl	2003	Herculex I
	Resistance[a] to corn rootworm	cry3Bb1	MoN863	Monsanto	2003	YieldGard (Rootworm)
		cry1Ab, cry3Bb1	MoN863 × MoN810	Monsanto	2005	YieldGard Plus

[a] Many insect resistance and herbicide tolerance traits are also available in combination as stack traits

7.21 Conclusions

Global warming and climate change will have serious consequences on diversity and abundance of arthropods and the extent of losses due to insect pests, which will impact both crop production and food security. Prediction of changes in geographical distribution and population dynamics of insect pests will be useful to adapt the pest management strategies to mitigate the adverse effects of climate change on crop production. Pest outbreaks might occur more frequently, particularly during extended periods of drought, followed by heavy rainfall. Some of the components of pest management such as host plant resistance, biopesticides, natural enemies, and synthetic chemicals will be rendered less effective as a result of increase in temperatures and UV radiation and decrease in relative humidity. Climate change will also alter the interactions between the insect pests and their host plants. As a result, some of the cultivars that are resistant to insect pests may exhibit susceptible reaction under global warming. Adverse effects of climate change on the activity and effectiveness of natural enemies will be a major concern in future pest management programs. Rate of insect multiplication might increase with an increase in CO_2 and temperature. Therefore, there is a need to have a concerted look at the likely effects of climate change on crop protection and devise appropriate measures to mitigate the effects of climate change on food security.

Serious consequences of climate change on diversity and abundance of insect pests and the extent of crop losses and food security for the twenty-first century are the major challenges for humankind in years to come. Being a tropical country, India is more challenged with impacts of looming climate change. In India, pest damage varies in different agroclimatic regions across the country mainly due to differential impacts of abiotic factors such as temperature, humidity, and rainfall. This entails the intensification of yield losses due to potential changes in crop diversity and increased incidence of insect pests due to changing climate. It will have serious environmental and socioeconomic impacts on rural farmers whose livelihoods depend directly on the agriculture and other climate-sensitive sectors.

Dealing with climate change is really a tedious task owing to its complexity, uncertainty, unpredictability, and differential impacts over time and place. Understanding insect pests and their natural enemies is an important and challenging topic ahead in agricultural research. Impacts of climate change on crop production mediated through changes in populations of serious insect pests need to be given careful attention for planning and devising adaptation and mitigation strategies for future pest management programs.

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Impacts on Plant Pathogens

8

Abstract

Changes in atmospheric composition and global climate continue in the future as predicted, there will be relocation of crops and their diseases and impacts will be felt in economic terms from crop loss. Changes in levels of CO_2, ozone, and UV-B will influence disease by modifying host physiology and resistance. In addition, changes in temperature, precipitation, and the frequency of extreme events will influence disease epidemiology. Changes in geographical distribution will potentially alter the relative importance and spectrum of diseases, and new disease complexes may arise. Evolution of pathogen populations may accelerate from enhanced UV-B radiation and/or increased fecundity in elevated CO_2. As a result, host resistances may be overcome more rapidly. Disease management will be influenced due to altered efficacy of biological and chemical control options. Given the multitude of atmospheric and climatic factors, possible change scenarios, and the number of disease systems, modeling approaches to impact assessment need to be strengthened. Changes in both mean temperature and its variability are equally important in predicting the potential impact of climate change. Given that climate change is a global issue, the focus needs to shift from paddock-based assessment on specific diseases to a more ecologically relevant spatial unit to consider climate with other associated changes in land use and vegetation cover, among others.

Keywords

Climate change • Impact on plant diseases • Geographical ranges • Adaptation • Mitigation

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Plant diseases are considered an important component of plant and environmental health and can be caused by infectious or biotic pathogens. Biotic plant diseases are caused by organisms such as fungi, bacteria, viruses, and phytoplasmas.

8.1 Crop Losses

Agricultural trends are influencing the incidence and importance of plant pathogens. First, the expansion of worldwide trade in food and plant products is spreading the impact of diseases. Second, changes in cultural techniques, particularly intensification of cropping, reduction in crop rotations, and increase in monocultures, encourages the activity of pathogens.

In extreme cases, pathogen damage can lead to severe impacts on society. In such cases, the climate conditions are conducive to widespread pathogen epidemics. The late blight of potato, caused by the fungus *Phytophthora infestans*, was a major factor in the Irish famine of the 1840s. Genetic uniformity of the potatoes was also a contributing factor. Late blight is still one of the most important diseases of potato and its epidemics continue to be highly correlated to weather conditions during sporulation. This disease presents a threat in the USA today.

Plant diseases are significant constraints to the production of some 25 crops that stand between the rapidly expanding world population and starvation (Wittwer 1995). Worldwide losses from diseases range from 9 to 16 % in rice, wheat, barley, maize, potato, soybean, cotton, and coffee, and in the USA alone, fungicides worth over US$5 billion are used to control diseases (Oerke et al. 1994). In Australia, diseases cost an estimated Au$1.3 billion annually in the six major agricultural commodities which are worth over Au$10.9 billion (Chakraborty et al. 1998). The economic impact of disease stems from losses in productivity, the cost of disease management, and the economic penalty paid for having to grow less profitable alternative crops. Diseases such as Panama wilt have resulted in the abandonment of entire banana plantations in Central America. The Irish potato blight (1845–1846) and the Bengal famine (1943) are grim reminders of the fact that the sociopolitical repercussions of major epidemics go far beyond simple economic impacts (Padmanabhan 1973).

Almost 100 years after the potato famine in Ireland, another fungus, *Helminthosporium oryzae*, the cause of brown spot of rice, precipitated another catastrophe in Bengal (now part of India and Bangladesh). In 1943 the weather conditions were exactly right to encourage an epidemic of the disease. Losses were extreme, often rising to 90 % or causing total destruction of the rice crop. Malnutrition and starvation caused the death of over 2 million people.

The southern corn leaf blight epidemic of 1970 and 1971 was the most dramatic epidemic in the history of agriculture in the USA. Just as genetic uniformity of the potato crop in Ireland, together with the spread of a virulent pathogen, led to the Irish potato famine in the last century, a similar combination of events brought about the southern corn leaf blight epidemics of 1970 and 1971. Crop production losses were even greater, but, since they occurred in the USA where the agricultural industry is highly diversified, human suffering occurred.

The grayish black rot caused by a fungus (*Helminthosporium maydis*) was found in October 1969 on corn ears and stalks samples from a seed field in Iowa. The following year, the epidemic struck. The disease first occurred in Mississippi in May of 1970 and rapidly spread northward through the Midwest on the air currents of a tropical storm in the Gulf of Mexico. Because 85 % of the corn was susceptible to the pathogen and the weather conditions were favorable for pathogen reproduction and dispersal, a dramatic epidemic occurred across the Corn Belt within 2 months, causing a 15 % decrease in national corn yields. The disease was most severe in the Midwest and south of the USA, with some areas reporting 50–100 % losses. For the nation as a whole, losses were officially estimated at the time as $1.09 billion. Although genetic uniformity in the corn crop contributed to the widespread occurrence of this disease, favorable meteorological conditions allowed it to occur.

Aflatoxin, a compound that lowers corn quality, is related to drought conditions. The concentration of aflatoxin is raised during crop-water deficits, because drought favors the growth

Table 8.1 Estimated potential of pathogens (bacteria, fungi, and viruses) and actual losses in six major crops worldwide, in 2001–2003 (Oerke 2006)

Crop	Attainable production (million tons)	Crop losses (%) due to pathogens			
		Pathogens		Viruses	
		Potential	Actual	Potential	Actual
Wheat	785.0	15.6 (12–20)	10.2 (5–14)	2.5 (2–3)	2.4 (2–4)
Rice	933.1	13.5 (10–15)	10.8 (7–16)	1.7 (1–2)	1.4 (1–3)
Maize	890.8	9.4 (8–13)	8.5 (4–14)	2.9 (2–6)	2.7 (2–6)
Potatoes	517.7	21.2 (20–23)	14.5 (7–24)	8.1 (7–10)	6.6 (5–9)
Soybeans	244.8	11.0 (7–16)	8.9 (3–16)	1.4 (0–2)	1.2 (0–2)
Cotton	78.5*	8.5 (7–10)	7.2 (5–13)	0.8 (0–2)	0.7 (0–2)

*Seed cotton

of the fungus *Aspergillus flavus* (the producer of aflatoxin) in the weakened crop. Similarly, wheat scab caused by *Fusarium* spp. produces mycotoxin in contaminated grain. Mycotoxin can produce muscle spasms and vomiting in humans. The emergence of wheat scab in the Great Plains may be linked to the increase in temperatures observed in key agricultural areas of this region during the past 10 years.

Climate change may lead to more incidence of insect-transmitted plant diseases through range expansion and rapid multiplication of insect vectors (Sharma et al. 2010). Increased temperatures, particularly in early season, have been reported to increase the incidence of viral diseases in potato due to early colonization of virus-bearing aphids, the major vectors for potato viruses in Northern Europe (Robert et al. 2000).

The comprehensive effort to provide a measure of global crop losses by diseases is made by Oerke (2006) (Table 8.1). They analyzed data on pest damage in six important food and cash crops. The estimate of preharvest loss caused by pathogens to the principal food and cash crops is 16 % of potential production on a global basis.

8.2 Climate Change and Plant Disease

The global climate change, especially increased levels of CO_2 and temperature (Pachauri and Reisinger 2007), is thought to influence or change all the elements of a disease triangle, viz., host, pathogen, and weather factors and their interactions (Fig. 8.1) (Legreve and Duveiller 2010). Both climatic variability and climate change are the relevant drivers of plant disease epidemics and are expected to alter the synchrony between crop phenology and disease patterns. This change in climatic patterns also affects the spatial distribution of agroecological zones, habitats, and distribution patterns of plant diseases which can have significant impacts on food production.

Whatever may be the reason, be it climate change, global change, or shifts in seasonality, changes in disease situations have already been experienced as some minor diseases have become major diseases in the Indian subcontinent. Current shift in the disease scenario in India, especially in rice and wheat, is a case in point. In rice, bacterial leaf blight (*Xanthomonas oryzae* pv. *oryzae*) has become a global biotic threat despite constant efforts to improve resistance through exploitation of host R-gene. Sheath blight (*Rhizoctonia solani*) and tungro virus that were of minor importance, have emerged as major problems in most of the rice-growing areas. Spot blotch (*Bipolaris sorokiniana*), once unknown or of minor importance, has become a serious problem in wheat. Increasing trend in winter temperature probably provides a favorable situation to the spot blotch in the Northwestern India (Duveiller et al. 2007). Dry root rot (*Rhizoctonia bataticola*) in chickpea is becoming more severe in the rainfed environments due to moisture stress and higher temperatures (Pandey et al. 2010). Excess moisture on the other hand is favoring some of the dreaded soilborne diseases caused by *Phytophthora*, *Pythium*, *Rhizoctonia solani*, and *Sclerotium rolfsii*, especially in pulses (Sharma et al. 2010).

Quantitative analysis of climate change is largely lacking from field, laboratory, or modeling-based

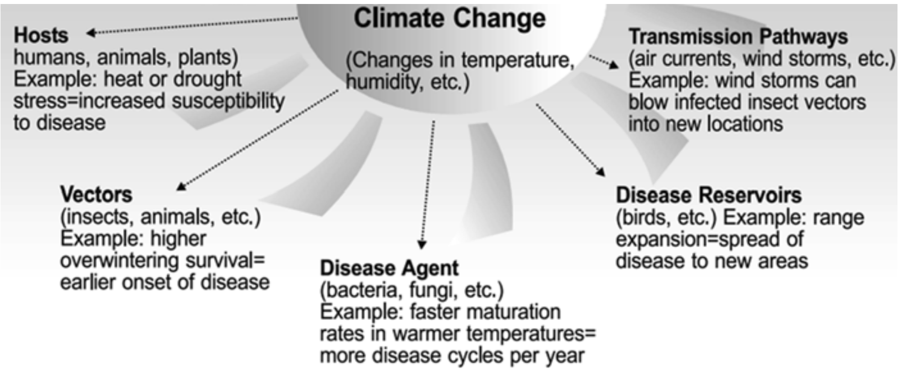


Fig. 8.1 The effects of climate change on the many components that make up a disease system can be positive or negative

assessments. The plant pathologists should provide long-term as well as short-term climate change adaptation measures to reduce the risk of crop loss due to sudden emergence of diseases so far unknown or economically negligible. Therefore, regular disease monitoring and surveillance is important since disease management does not work like fire fighting. Disease risk in advance requires for short-term or tactical disease management, and disease scenario based on climate forecasts are to be the basis of future strategies. Identifying and quantifying the impacts of climate changes on plant diseases is a complex phenomenon (Coakley and Scherm 1996) as there is a great deal of uncertainty about the accurate climate forecast.

Crops can be damaged by diseases caused by fungi (rust, blight, mildew, rot), bacteria/phytoplasma (wilt), and viruses. The occurrence of plant fungal and bacterial pathogens depends on climate and weather. They are also strongly influenced by agricultural practices. Viruses and phytoplasma are often transferred via vectors, often insects. Temperature, rainfall, humidity, radiation, or dew can affect the growth and spread of fungi and bacteria (Patterson et al. 1999). Other important factors influencing plant diseases are air pollution, particularly ozone and UV-B radiation (Manning and von Tiedemann 1995) as well as nutrient (especially nitrogen) availability (Thompson et al. 1993).

Climate factors that influence the growth, spread, and survival of crop diseases include temperature, precipitation, humidity, dew, radiation, wind speed, circulation patterns, and the occurrence of extreme events. Typically, the two most important environmental factors in the development of plant disease epidemics are temperature and moisture. In temperate regions, most plant pathogens are not active in late fall, winter, and early spring because of low temperatures. Some diseases are favored by cool temperatures, while others are favored by moderate or hot conditions. Disease often occurs when temperatures are more stressful for the plant than for the pathogen. Moisture, in the form of free water or high humidity, is necessary for many pathogens to infect, reproduce, and spread, although some can cause disease in dry conditions. Plant diseases require varying environmental conditions to develop; thus, it is vital to understand the environmental requirements of individual plant pathogens before predicting responses to climate change (Fig. 8.2).

Higher temperature and humidity and greater precipitation result in the spread of plant diseases, as wet vegetation promotes the germination of spores and the proliferation of fungi and bacteria and influences the life cycle of soil nematodes. In regions that suffer aridity, however, disease infestation lessens, although some diseases (such as the powdery mildews) thrive in hot, dry conditions, as long as there is dew formation at night.

Environmental factors dramatically affect the development of plant diseases. Plant pathologists often use a disease triangle to illustrate the intimate relationship among plants, pathogens, and the environment. For a plant disease to develop, a susceptible host, a virulent pathogen, and a suitable

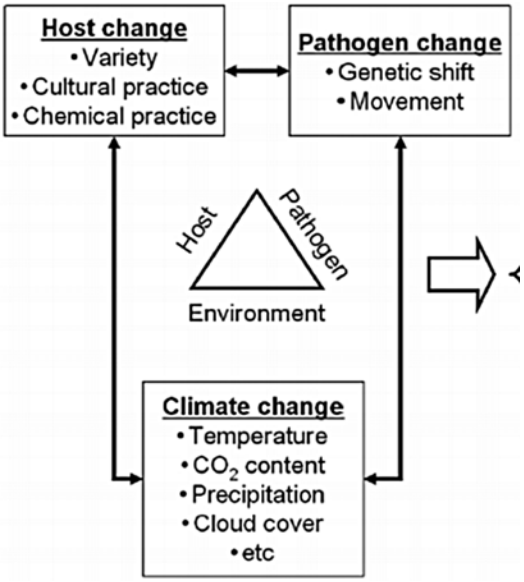


Fig. 8.2 Interactions among factors in disease triangle

environment must occur simultaneously. Because of this intimate relationship among plants, pathogens, and the environment, climate change is expected to affect the incidence and severity of plant disease. The classic disease triangle recognizes the role of climate in plant diseases as no virulent pathogen can induce disease on a highly susceptible host if climatic conditions are not favorable. Climate influences all stages of host and pathogen life cycles as well as development of disease. Disease severity over a period can fluctuate according to climatic variation.

It is likely that climate change will have positive, negative, or neutral impacts on specific host–pathogen systems (Coakley et al. 1999; Chakraborty et al. 2000b). In general, climate change has the potential to modify host physiology and resistance and to alter stages and rates of development of the pathogen (Coakley et al. 1999).

8.3 CO_2 Enrichment

Photosynthesis, leaf area, plant height, total biomass (shoot and root) and crop yield, sugar and starch content, water-use efficiency, growth, and yield are increased in the presence of higher levels of CO_2. These effects often result in changed plant architecture and the development of larger plant organs. Because many foliar pathogens can take advantage of the more humid microclimate caused by denser plant growth and the higher availability of host tissue, pathogen infection rates of these pathogens usually increase at higher CO_2 levels. However, the final effect of increased CO_2 concentrations on the disease depends on the interaction between the effects on the pathogen and the effects on the plant under the specific environmental conditions.

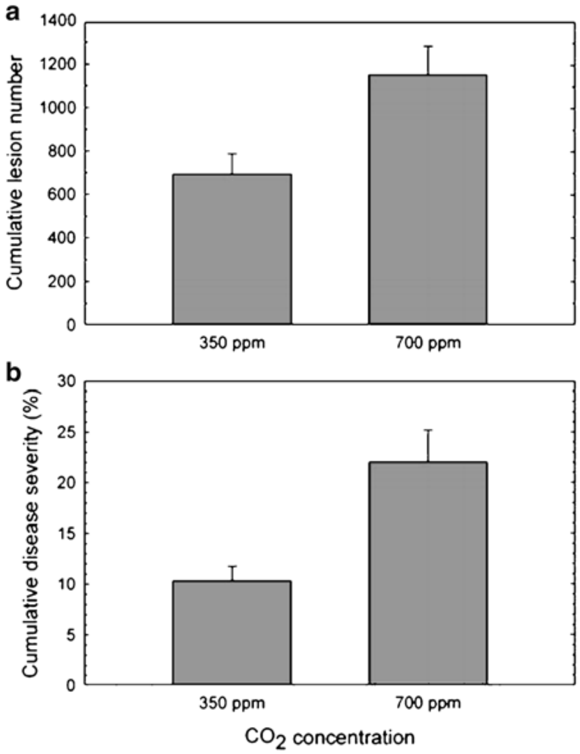
Elevated CO_2 may increase C3 plant canopy size and density, resulting in a greater biomass with a much higher microclimate relative humidity. This is likely to promote plant diseases such as rusts, powdery mildews, leaf spots, and blights (Manning and von Tiedemann 1995). However, Kobayashi et al. (2006) conclude from literature reviews that it is not clear whether the disease severity is enhanced or diminished by a higher CO_2 level. Research on rice leaf blast and rice sheath blight in the temperate climates of Japan showed that elevated CO_2 increased the potential risks for infection from leaf blast and epidemics of sheath blight (Kobayashi et al. 2006).

In soybeans, elevated CO_2 alone or in combination with ozone (O_3) significantly reduced downy mildew (*Peronospora manshurica*) disease severity by 39–66 % across a 3-year study. In contrast, elevated CO_2 alone or in combination with O_3 significantly increased brown spot (*Septoria glycines*) severity, but the increase was small in magnitude (Eastburn et al. 2009).

In wheat, grown at elevated atmospheric CO_2 (700 ppm) and under different fertilization and water regimes, the host water content, the plant N content, and the infection rate with powdery mildew were investigated. In all fertilization regimes, the mean percent leaf area infected with mildew was significantly reduced under elevated atmospheric CO_2, compared to ambient CO_2.

In a moderate water supply treatment (3.6 mm/day), the plants grown in elevated atmospheric CO_2 concentrations had significantly reduced N contents (9.9 %) and significantly increased water content (4 %), and the amount of mildew infection was unchanged. At higher water supply (5.4 mm/day), host water

Fig. 8.3 Cumulative number of lesions (**a**) and disease severity expressed as percent leaf area affected (**b**) caused by *Colletotrichum gloeosporioides* on susceptible *Stylosanthes scabra* plants



content at elevated CO_2 was similar to that of ambient CO_2, but N content was significantly reduced. As a consequence, severity of powdery mildew caused by *Erysiphe graminis* infection was significantly reduced, compared to ambient CO_2. At lower water supply (1.8 mm/day), the results were quite different. Host water content at elevated CO_2 was higher compared to that of ambient CO_2, but N content showed no difference. As a consequence, severity of powdery mildew infection was significantly increased, compared to ambient CO_2. It seems that severity of mildew infection is more sensitive to host water content than to host nitrogen content (Thompson et al. 1993).

Astonishing results were gained in an experiment on oat (*Avena sativa*) grown under elevated CO_2 (700 ppm) and infected by barley yellow dwarf virus (BYDV). Root mass of virus-infected plants increased by 37–60 % with CO_2 enrichment but was largely unaffected in healthy plants. CO_2 enrichment increased photosynthesis and water-use efficiency by 34 and 93 % in healthy plants and by 48 and 174 % in infected plants – basically the infected plant performed better under elevated CO_2 than at ambient CO_2 (Malmstrom and Field 1997).

Chakraborty et al. (2000a, b) studied dispersal of and infection by *Colletotrichum gloeosporioides* under ambient weather conditions in the field on *Stylosanthes scabra* plants that had been raised under 1x or $2xCO_2$ in controlled environment chambers. Plants from the two CO_2 environments were exposed to naturally occurring inoculum in the field on different dates, and conidial dispersal and infection were monitored. The enlarged canopy of plants grown under elevated CO_2 trapped more conidia that, together with increased humidity in the denser canopy, led to more severe anthracnose than on plants grown under $1xCO_2$ (Fig. 8.3).

Decomposition of plant litter is important for nutrient cycling and in the saprophytic survival of many pathogens. Because of high C:N ratio of litter as a consequence of plant growth under elevated CO_2, decomposition will be slower. Increased plant biomass, slower decomposition of litter, and higher winter temperature could increase pathogen survival on overwintering crop residues and increase the amount of initial inoculation available for subsequent infection and earlier and faster disease epidemics.

Some fungal pathosystems under elevated CO_2 revealed two important trends. First, delay in the initial establishment of the pathogen because of modifications in pathogen aggressiveness and/or host susceptibility. For example, reduction in the rate of primary penetration of *Erysiphe graminis* on barley and a lengthening of latent period in *Maravalia cryptostegiae* (rubber vine rust) has been observed under elevated CO_2. Here, host resistance may have increased because of change in host morphology, physiology, nutrients, and water balance. A decrease in stomatal density increases resistance to pathogens that penetrate through stomata. Under elevated CO_2, barley plants were able to mobilize assimilates into defense structures including the formation of papillae and accumulation of silicon at sites of appressorial penetration of *E. graminis*.

At elevated CO_2, increased partitioning of assimilates to roots occurs consistently in crops such as carrot, sugar beet, and radish. If more carbon is stored in roots, losses from soilborne diseases of root crops may be reduced under climate change. In contrast, for foliage diseases favored by high temperature and humidity, increases in temperature and precipitation under climate change may result in increased crop loss. The effects of enlarged plant canopies from elevated CO_2 could further increase crop losses from foliar pathogens.

The second important effect is an increase in the fecundity of pathogens under elevated CO_2. Following penetration, established colonies of *Erysiphe graminis* grew faster, and sporulation per unit area of infected tissue was increased severalfold under elevated CO_2. It has been also observed that under elevated CO_2 out of the 10 biotrophic pathogens studied, disease severity was enhanced in six and reduced in four and out of 15 necrotrophic pathogens, disease severity increased in nine, reduced in four, and remained unchanged in the other two (Chakraborty et al. 1998).

It has been observed that oats infected with Barley yellow dwarf virus (BYDV) showed greater biomass accumulation to CO_2 enrichment than the healthy plant. Tobacco plants grown at increased CO_2 concentrations showed a markedly decreased spread of virus. It appears that CO_2 rise in the air may have some positive effects, which may likely offset the negative effects of virus infection.

Some diseases can cause more severe reduction in plant growth under twice ambient compared to ambient CO_2 at least in controlled environments. For example, in barley powdery mildew, an acclimation of photosynthesis at elevated CO_2 and an infection-induced reduction in net photosynthesis caused larger reductions in plant growth at elevated CO_2 (Hibberd et al. 1996b).

Thompson et al. (1993) reported a significant reduction in wheat powdery mildew at twice-ambient CO_2, but final severity was dependent on nitrogen and water status of plants.

Pathogen growth can be affected by higher CO_2 concentrations resulting in greater fungal spore production. However, increased CO_2 can result in physiological changes to the host plant that can increase host resistance to pathogens (Coakley et al. 1999).

Despite initial delays and reduction in host penetration, established colonies grow faster inside host tissues at elevated CO_2 (Hibberd et al. 1996a; Chakraborty et al. 2000a, b). Fecundity of both biotrophs and necrotrophs (Chakraborty et al. 2000a, b) studied so far has increased under elevated CO_2. A combination of increased fecundity and a favorable microclimate within enlarged canopies will provide more opportunities for infection. There is evidence of adaptation for increased aggressiveness in some pathogens (Kolmer and Leonard 1986) within three sexual generations, and controlled crossing has shown that aggressiveness is heritable and may be polygenically controlled (Caten et al. 1984). For sexually reproducing pathogen populations with broad genetic diversity, increased population size and the number of generations in favorable microclimates would increase the probability of more damaging pathotypes evolving more rapidly (Sutherst et al. 1996).

8.4 Elevated Temperatures

Harvell et al. (2002) considered the consequences of warmer temperatures on host–pathogen interactions and concluded that there will be three main effects:

Table 8.2 Possible effects of climate change on plant-pathogen survival

Survival mode of pathogen	Common types of pathogens	Effects of climate change
Disease organisms that survive in soil	Introduced diseases	Thick-walled spores and other survival structures produced by these pathogens should not be greatly affected by climate change
Disease organisms that survive in plants or plant debris	Introduced diseases	Milder winters could increase survival of pathogens that overwinter on living and dead plants
Disease organisms that are transferred by vectors	Viruses and fungi	Milder winters could increase survival of insect vectors; milder summers could result in increased development and reproductive rates
Introduced diseases	Introduced diseases	Pathogens that do not presently survive winters may do so if winters become milder

- Increases in pathogen development rate, transmission, and generations per year
- Increases in overwintering of pathogens
- Changes in host susceptibility to infection

Furthermore, they suggested that the most severe and unpredictable consequences would occur if populations of pathogen and host, which were formerly geographically separated due to climate constraints, converged.

Long and cold winters have reduced survival of organisms that cause disease, restricted the number of disease generations per year, and limited disease activity during the growing season. If the climate warms, these issues of disease survival, growth, and activity will change. For disease survival, climate change effects will depend on the way in which the pathogen presently survives adverse conditions (Table 8.2).

Increases in temperature can modify host physiology and resistance. Both temperature and the length of exposure are important in determining the effect of climate change on disease severity. Even if the temperature change may be well within the limits of current climatic variability, a modest warming can cause a significant increase in cumulative temperature above a critical temperature threshold to affect crop physiology and resistance to a disease. Temperature change might lead to appearance of different races of the pathogens hitherto not active but might cause sudden epidemic. Change in temperature will directly influence infection, reproduction, dispersal, and survival between seasons and other critical stages in the life cycle of a pathogen.

At higher temperature, lignification of cell walls increased in forage species and enhanced resistance to fungal pathogens. Impact would, therefore, depend on the nature of the host–pathogen interactions and mechanism of resistance. A rise in temperature above 20 °C can inactivate temperature-sensitive resistance to stem rust in oat cultivars. Increase in temperature with sufficient soil moisture may increase evapotranspiration, resulting in humid microclimate in crop canopy, and may lead to incidence of diseases favored under warm and humid conditions. Some of the soilborne diseases may increase at the rise of soil temperature. If climate change causes a gradual shift of cropping regions, pathogens will follow their host. Analysis of long-term data of wheat and rice diseases in China has shown trends of an increase in minimum temperatures in association with the abundance of rice blast or wheat scab. In most locations, temperature changes had significant effects on disease development. However, these effects varied between different agroecological zones. In cool subtropical zones such as Japan and northern China, elevation of ambient temperature resulted in greater risk of blast epidemics. Situations in the humid tropics and warm humid subtropics were opposite to those in cool areas. A lower temperature resulted in greater risk of blast epidemics.

Temperature has potential impacts on plant disease through both the host crop plant and the pathogen. Research has shown that host plants such as wheat and oats become more susceptible to rust diseases with increased temperature; but some forage species become more resistant to fungi with increased temperature (Coakley et al. 1999). Many mathematical models that have been useful for forecasting plant disease epidemics are based on increases in pathogen growth and infection within specified temperature ranges. Generally, fungi that cause plant disease grow best in moderate temperature ranges. Temperate climate zones that include seasons with cold average temperatures are likely to experience longer periods of temperatures suitable for pathogen growth and reproduction if climates warm. For example, predictive models for potato and tomato late blight (caused by *Phytophthora infestans*) show that the fungus infects and reproduces most successfully during periods of high moisture that occur when temperatures are between 7.2 and 26.8 °C (Wallin and Waggoner 1950). Earlier onset of warm temperatures could result in an earlier threat from late blight with the potential for more severe epidemics and increases in the number of fungicide applications needed for control.

A simulation model was developed for rice leaf blast epidemics in Japan, China, Thailand, South Korea, and the Philippines under increasing temperature and ultraviolet-B (UV-B) radiation. Elevated CO_2 was not considered. The simulation showed that in the cooler regions of Japan and northern China, a temperature increase might lead to more severe blast epidemics, while in humid tropics and warm humid tropics, this risk might decrease. The authors concluded that in these regions, blast development is inhibited by high temperatures. UV-B radiation will enhance the severity of blast, but more in cooler than in warmer regions (Luo et al. 1995).

Kaukoranta (1996) simulated yield loss in potato based on a 3-year-long controlled environment study of late blight at ambient temperature and at 3 °C higher than ambient. This study suggested that increases in yield loss of unprotected potato crop at the high temperature would wipe out any benefits from yield increases of around 2 t/ha dry matter per degree of warming.

Agricultural crops and plants in natural communities may harbor pathogens as symptomless carriers (Dinoor 1974), and disease may develop if plants are stressed in a warmer climate. Host stress is an especially important factor in decline of various forest species. Climate extremes such as drought may increase invasion by *Armillaria* spp. that are not normally very pathogenic (Lonsdale and Gibbs 1996). High temperatures may increase the damage caused by diseases such as Scleroderris canker on lodgepole pine (Lonsdale and Gibbs 1996). Such projections, however, do not consider other factors that can enhance the resilience of forest ecosystems to climate change, which led Loehle (1996) to conclude that there is “a systematic bias toward alarmist predictions” in projections of tree health response to climate change.

Most plant viruses are transmitted by vectors and majority by insects. Particularly aphids are expected to react strongly to environmental changes because of their short generation time, low developmental threshold temperatures, and ability to survive mild winters without winter storms. An increase in the number of insect vectors will inevitably lead to a higher risk for viral infection of plants. The aphid transmissible complex of barley yellow dwarf viruses in cereals and potato virus Y in potato is amenable to show potential effects on the prevalence of infection because of climate change. In mild winters, high intensity of aphid movement during spring and a high frequency of PVY-infected potatoes have been reported. The severity of viral diseases is determined in large part by the amount of inoculum and the time of infection. The amount of virus inoculum is influenced by winter survival of its hosts. For some viruses, higher temperatures also cause more severe symptoms development. Aphids are expected to have increased survival with milder winter temperatures, and higher spring and summer temperatures will increase their development and reproductive rates and lead to more severe disease. Milder winters are also expected to increase survival of alternate weed hosts of viruses. Increases in frequency and intensity of summer storms with high winds, rain, and hail will increase wounding of plants and result in increased transmission of viruses by mechanical means. Therefore, with predicted changes in climate, viral diseases of plants are expected to increase in importance. Potentially of greater importance will be the effects of diseases caused by newly introduced viruses that, because of the changed climate, will be able to persist. A warmer climate might also allow viruses that are present in greenhouses, such as Pepino mosaic virus (PepMV), to establish infection in the field. The main effect of temperature in temperate regions is to influence winter survival of vectors. Natural spread of vectors, pests, and diseases is accelerated towards the north, as former climate barriers are no longer effective. This results in more severe outbreaks of plant disease vectors like aphids, whiteflies, thrips, or beetles, an extension of the period of disease infection further into the growing season and also introduction and establishment of new vector species. The described effects on vectors can have severe negative effects on food production or result in an increased use of plant protection products to control the vectors.

8.5 Varying Precipitation Patterns

Moisture can impact both host plants and pathogen organisms in various ways. Some pathogens such as apple scab, late blight, and several vegetable root pathogens are more likely to infect plants with increased moisture – forecast models for these diseases are based on leaf wetness, relative humidity, and precipitation measurements. Other pathogens like the powdery mildew species tend to thrive in conditions with lower (but not low) moisture.

More frequent and extreme precipitation events that are predicted by some climate change models could result in more and longer periods with favorable pathogen environments. Host crops with canopy size limited by lack of moisture might no longer be so limited and may produce canopies that hold moisture in the form of leaf wetness or high canopy relative humidity for longer periods, thus increasing the risk from pathogen infection (Coakley et al. 1999). Some climate change models predict higher atmospheric water vapor concentrations with increased temperature that would also favor pathogen and disease development.

Bacteria are spread to their host plants mainly by water, usually in the form of rain splash and insects. In humid, wet conditions, infected plant tissues can exude masses of bacteria that are spread from host to host by rain splash and insects. Therefore, the warmer drier summers expected with climate change should limit bacterial diseases. However, bacteria often enter hosts through wounds, and the expected increase in frequency and intensity of summer storms with high winds, rain, and hail will increase wounding of plants and provide moisture for the spread of bacteria.

8.6 Expansion of Geographical Distribution

With changes in climate, plants will migrate to new areas, and their pathogens will follow. How quickly pathogens migrate to follow host plants will depend on factors such as their dispersal mechanisms, suitability of the environment for dispersal to occur, survival between seasons, and changes in host physiology and ecology in the new environment. If a host is chronically stressed due to less than optimum conditions, its health would deteriorate and its susceptibility to disease would increase, particularly in perennials (Chakraborty et al. 1998). New diseases may establish in a region, while some established diseases may cease to be economically important. Although climate changes may reduce the suitability of a crop for a region, it may continue to be grown for agro-ecological or economic reasons.

The northward expansion of the soybean sudden death syndrome (a soilborne fungal disease caused by *Fusarium solani* f. sp. *glycines*) is an example (Roy et al. 1997). The disease was first reported in Arkansas in 1971; in the early 1980s, it was found in southern Missouri, Illinois, and Indiana; by the early 1990s, it was also found in southern Iowa, northern Illinois, and northern Indiana; and in 1998 it was found in Ontario, Wisconsin, and Ohio.

Table 8.3 Major crop diseases that appeared after 1970 in the USA

Crop	Disease causal agent	Expansion
Soybean	Sudden death syndrome, *Fusarium solani* f sp. *glycines*	Appeared in Arkansas in 1971 and has spread to the northern soybean region as far as Ontario
	Southern stem canker, *Diaporthe phaseolorum*	First observed in 1973, has developed into a devastating disease in the southern production region
	Sclerotinia stem rot, *Sclerotinia sclerotiorum*	Reemerged as a leading disease in 1990 in the north central soybean regions
	Soybean cyst nematode, *Heterodera glycines*	Expanded to northern soybean regions
Corn	Gray leaf spot, *Cercospora zeae-maydis*	First reported in the 1940s, became a concern in the 1970s in the eastern states, and now is a major concern in the Corn Belt
Potato	Late blight, *Phytophthora infestans*	Reemerged in 1990 as a new threat to potato production after a new mating type was found in Mexico
	Powdery scab, *Spongospora subterranea*	Increased damage in Washington and Oregon
Rice	Sheath blight, *Rhizoctonia solani*	Major rice disease worldwide since the 1970s
Wheat	Wheat scab, *Fusarium* spp.	Reemerged after 1990 as a leading wheat disease in the central and north regions
	Barley yellow dwarf, Barley yellow dwarf virus	Listed by 14 wheat production states as a recently emerging disease

Source: Plant Pathology Department, North Carolina State University

The gray leaf blight of corn caused by the fungus *Cercospora zeae-maydis* ranks number one in causing yield losses of corn in recent years. It is also a disease whose range expansion was first noticed in the 1970s; in the last two decades, the disease has gradually developed into a major production problem in the Corn Belt. Although the increase in the abundance and epidemics of this disease may be due, in part, to the increase in the use of conservation tillage, the observed trends in minimum temperatures and precipitation in the region may also have contributed.

Among the earliest attempts to relate historic records of meteorological conditions and crop pest damage were the studies of potato leaf roll outbreaks in North America and Europe. Analysis of the historic records from 1930 to 1991 suggests that the outbreaks of this aphid-borne viral disease were related to drought and sunspot cycles. In the USA, the frequency of the reported outbreaks seems to have increased since 1970 (Table 8.3).

Another example of the linkage between meteorological variables and pests is the wheat stem rust disease in the US Great Plains. The epidemics of the disease from 1921 to 1962 seem to be related to the conditions during El Niño episodes (Yang and Scherm 1997). In contrast, wheat stripe rust epidemics in the US Northwest may be more severe during La Niña years (Scherm and Yang 1995).

Warming will generally cause a pole-ward shift of the risk of damage from late blight of potato which would increase in all regions and potato nematodes may become a serious problem with additional generations per year. Similar predictions of northward migration and increased severity in areas of current distribution have been made for the oak decline pathogen, *Phytophthora cinnamomi* (Brasier and Scott 1994; Brasier 1996). Pathogens will follow migrating host plants and their dispersal and survival between seasons, and changes in host physiology and ecology in the new environment would largely determine how rapidly the pathogens establish in the new environment.

Pathogens, in particular unspecialized necrotrophs, may extend their host range to cause new disease problems in migrating crops. There are at least two well-known examples of an indigenous pathogen attacking an introduced plant when grown in close proximity. In its native habitat in the USA, the fire blight bacterium, *Erwinia amylovora*, attacks indigenous plants of the family Rosaceae without causing significant damage. When European settlers grew apples and pears in some regions, the bacterium caused serious losses. Similarly, the coffee rust epidemic in Asia during the late 1800s was facilitated by growing an introduced susceptible host, *Coffea arabica*, in a region where the native pathogen, *Hemileia vastatrix*, was already present on alternative hosts in the forests outlining the coffee plantations (Carefoot and Sprott 1967). Expansion of host range may even occur in specialized biotrophs, as geographical proximity is as important as phylogenetic relatedness in influencing the host range of some rusts (Savile and Urban 1982). As plants in both natural and agricultural communities can be symptomless carriers of pathogens, any early predictions of impending damage will be difficult (Dinoor 1974).

8.7 Elevated Levels of Atmospheric Pollutants

8.7.1 Ozone

Ozone is considered to be the most phytotoxic of the common air pollutants. It can cause chlorotic and necrotic lesions on sensitive plant species, and even in the absence of visible symptoms, photosynthesis and growth can be inhibited. Ozone damage can lead to reduced competitive fitness of plants, and reduced vitality makes plants more susceptible to plant pathogens (Sandermann 2000). Direct effects of ozone on fungal pathogens are not significant (Manning and von Tiedemann 1995), although interactions between ozone damage and infection by *Alternaria solani*, the causal agent of early blight of potato, have been reported (Holley et al. 1985a, b). Researchers have reported both increased (Sandermann 2000) and decreased (Coleman et al. 1988) disease susceptibility in plants after ozone exposure. According to von Tiedemann and Firsching (2000), ozone effects on plant disease susceptibility may be strongly altered by interfering factors such as plant developmental stage, nutrient supply, and other atmospheric trace gases.

Most air pollutants indirectly influence diseases through their effect on host. Ozone induces reactions similar to those normally elicited by viral and other pathogens. Of the 49 bacteria and fungal pathogens examined, exposure to elevated ozone concentration enhanced disease in 25, did not affect 10, and reduced 14. Pollutant concentrations, which inhibit pathogen development, also injure the host. Similarly, infection by plant pathogens can alter ozone sensitivity of plants. Exposure to 5–10 ppm ozone for a few hours can cause visible injury to sensitive crops like barley, tomato, onion, potato, soybean, tobacco, and wheat.

Elevated ozone concentrations may change the structure and properties of leaf surfaces in ways that may affect the inoculation and infection process. Ozone enhances senescence processes, may encourage necrosis, and seems to promote attacks on plants by necrotrophic fungi.

Current climate change scenarios predict a further increase of tropospheric ozone, which is well known to inhibit plant photosynthesis and growth process. Ozone can also predispose plants to enhanced biotic attack, as proposed in particular for necrotrophic fungi, root rot fungi, and black beetles. However, at present it does not seem possible to predict whether increased ambient ozone will lead to higher or lower disease likelihood in particular plant-pathogen system. Several root pathogens show a preference for stressed trees, although the direct role of ozone is not always evident. Onions injured by ozone exposure were more susceptible to *Botrytis cinerea*, but not to *B. squamosa*. Increased onion yields and reduced dieback when filters removed ambient ozone have been also observed in some experimental studies.

8.7.2 Acid Rain

Most studies on the effect of acid rain were done with simulated acid rain since it is not easy to establish experiments under field conditions. In first year of experiment, no effect of acid rain has been observed on any of four pathosystems: alfalfa leaf spot, peanut leaf spot (PLS), potato late blight (PLB), and soybean brown spot. In the second year, PLS severity decreased with increasing acidity and the dose response was linear; PLB severity showed a curvilinear response to acid rain.

8.7.3 Elevated Ultraviolet-B

Ultraviolet (UV) light has long been known to influence plant pathogenic fungi. This light may stimulate spore production in a wide range of fungi but may also reduce spore survival during dispersal or early stages of infection (Paul et al. 1998). Although an increase in solar UV-B radiation due to ozone depletion could promote sporulation of pathogenic fungi in a way that could greatly increase the frequency and intensity of epidemics, normal daylight already contains enough UV light to stimulate sporulation of light-dependent fungi.

There is considerable information on the effects of increased UV-B on crops and natural vegetation and on the growth and life cycle of pathogenic organisms such as fungi. Studies indicate that the UV-B component of solar radiation plays a natural regulation on plant diseases. Stimulatory effect of near-UV light on reproduction of many fungi and spore production in *Leptosphaerulina trifolii* peaks at 287 nm are reported. Fungi differ in their sensitivity to UV-B. Some strains of *Septoria tritici* are more sensitive to UV-B than others, and *S. nodorum*, as a species, is more sensitive than *S. tritici*. UV-B radiation can modify the relative composition of phylloplane organisms, such as pink and white yeast. Continued exposure to enhanced UV-B radiation lowers the level of antifungal compounds in foliar parts. UV-B has been shown to reduce tolerance of rice to blast (*Pyricularia grisea*) and although higher UV-B reduced plant biomass and leaf area, there was no increase in blast severity. There are some evidences that sunlight can influence pathogen by causing accumulation of phytoalexins or protective pigments in plant tissues. Therefore, UV-B may affect plant diseases directly via the pathogen or indirectly via the host.

8.8 Disease Management

Climate change can affect disease management by altering efficacy of biological and chemical control options (Chakraborty et al. 1998; Coakley et al. 1999). For example, heavy rains reduce fungicide residue. Crop plants growing under elevated CO_2 could be altered morphologically or physiologically, affecting uptake, translocation, and metabolism of systemic fungicides. For example, increased thickness of the epicuticular wax layer on leaves could result in slower and/or reduced uptake by the host, while increased canopy size could negatively affect spray coverage. Conversely, if higher temperatures increase plants' metabolic rates, they may take up chemicals more quickly, which may result in greater toxicity (Coakley et al. 1999).

New dimensions of climate change may add extra uncertainty in management strategies for diseases caused by different pathogens. Impacts of climate change on plant pathosystems would occur chiefly through influences on host resistance or chemical and biological control agents. Delayed planting to avoid a pathogen may become less reliable. Particular attention is needed to identify cases where the efficacy of disease management may be reduced under climate change.

8.8.1 Host Resistance

Cultivar resistance to pathogens may become more effective because of increased static and dynamic defenses from changes in physiology, nutritional status, and water availability. Durability of resistance may be threatened, however, if the number of infection cycles within a growing season increases because of one or more of the following factors: increased fecundity, more pathogen generations per season, or a more suitable microclimate for disease development. This may lead to more rapid evolution of aggressive pathogen races. In a pilot study, evolution of *Colletotrichum gloeosporioides* on *Stylosanthes scabra* under elevated CO_2 was monitored. A susceptible cultivar was grown in a controlled environment under 1x or 2xCO_2 and inoculated with three isolates of the pathogen. For each isolate, conidia collected from infected host tissue were used to inoculate a second group of plants of the same cultivar. Successive groups of plants were

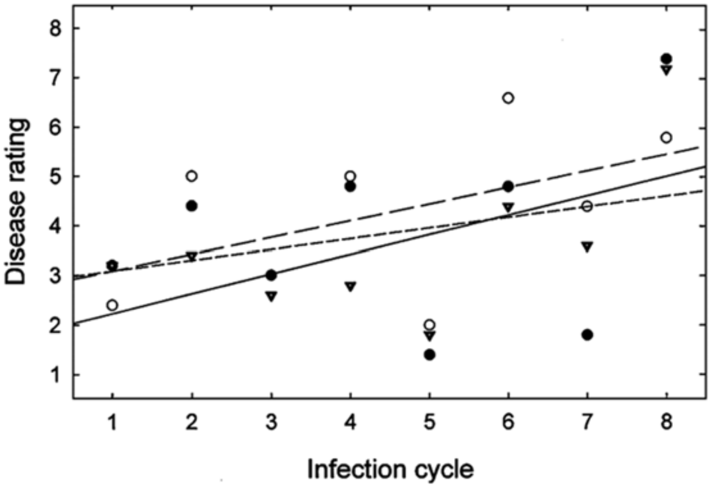


Fig. 8.4 Disease severity (on a scale from 0 to 9) caused by *Colletotrichum gloeosporioides* on susceptible *Stylosanthes scabra* plants under 2xCO_2 over eight cycles of infection. For each of the three isolates (indicated by different *symbols* and *lines*), successive groups of plants were inoculated with conidia arising from the previous infection cycle to simulate polycyclic disease development and pathogen evolution over time. The regression lines for the three isolates were significantly different from zero ($P < 0.05$)

inoculated with conidia arising from the previous infection cycle to simulate polycyclic disease development and pathogen evolution over time. After each cycle, measurements were made on components of pathogen aggressiveness, such as fecundity, lesion size, lesion number, and disease severity. Preliminary results suggested a significant trend towards increased disease severity (Fig. 8.4); further, two of the three isolates showed a gradual increase in fecundity under elevated CO_2 after eight infection cycles.

Elevated temperature may cause the breakdown of temperature-sensitive resistance in oat cultivars with Pg3 and 4 genes (Martens et al. 1967).

8.8.2 Chemical Control

Climate change could affect the efficacy of crop protection chemicals in one of two ways. First, changes in temperature and precipitation may alter the dynamics of fungicide residues on the crop foliage. Globally, climate change models project an increase in the frequency of intense rainfall events (Fowler and Hennessy 1995), which could result in increased fungicide wash-off and reduced control. Data from field experiments and modeling studies suggest precipitation during the post-application period (Schepers 1996) is critical. Precipitation following fungicide application may improve its distribution (Schepers 1996), but an increase in rainfall intensity can deplete fungicide residue on the foliage (Neuhaus et al. 1974). The interactions of precipitation frequency, intensity, and fungicide dynamics are complex, and for certain fungicides precipitation, following application may result in enhanced disease control because of a redistribution of the active ingredient on the foliage (Schepers 1996). Neuhaus et al. (1974) applied simulated rain to potato foliage at two intensities (6 and 30 mm/ha) and found that the higher rate significantly reduced the fungicide residue that could be measured with a chemical assay, but that there was no difference in disease between the two treatments when the leaves were challenged in a bioassay with *Phytophthora infestans*.

Second, morphological or physiological changes in crop plants resulting from growth under elevated CO_2 could affect uptake, translocation, and metabolism of systemic fungicides. For example, increased thickness of the epicuticular wax layer on leaves (Wolfe 1995) could result in slower and/or reduced uptake by the host, whereas increased canopy size could negatively affect spray coverage and lead to a dilution of the active ingredient in the host tissue. Both factors would suggest lowered control efficacy at higher concentrations of CO_2. Conversely, increased metabolic rates because of higher temperatures could result in faster uptake by and greater toxicity to the target organism. Despite the potential for important interactions, no similar studies evaluating the impacts of climate change variables on physiological aspects have been published for fungicides.

The more frequent rainfall events predicted by climate change models could result in farmers finding it difficult to keep residues of contact fungicides on plants, triggering more frequent applications. Systemic fungicides could be affected negatively by physiological changes that slow uptake rates, such as smaller stomatal opening or thicker epicuticular waxes in crop plants grown under higher temperatures.

8.8.3 Biological Control

There may be problems with applications of biocontrol agents in the field because of the vulnerability of biocontrol agent populations to environmental variations and environmental extremes. If appropriate temperature and moisture are not consistently available, biocontrol agent populations may reach densities that are too small to have important effects and may not recover as rapidly as pathogen populations when congenial conditions reoccur.

In the rhizosphere, elevated CO_2 would interact with nitrogen and other soil factors to modify the number and type of mycorrhizal fungi to influence root health and nutrient uptake. Some short-term studies under controlled conditions have shown that elevated CO_2 can stimulate mycorrhizal colonization (Staddon and Fitter 1998) due to faster plant growth. Colonization of roots by arbuscular mycorrhizal fungi is favored in soils of poor nutritional status (Klironomos et al. 1997). It is not clear if increases in soil carbon storage due to greater root and mycorrhizal growth under high CO_2 will influence mycorrhizal colonization.

8.8.4 Microbial Interactions

Climate change may alter the composition and dynamics of microbial communities in aerial and soil environments sufficiently to influence the health of plant organs (Gunasekera et al. 1997). Changed microbial population in the phyllosphere and rhizosphere may influence plant disease through natural and augmented biological control agents. A direct effect of elevated CO_2 is unlikely in the soil environment as the microflora there is regularly exposed to levels 10–15 times higher than atmospheric CO_2.

Trees grown in soils of poor nutrient status, especially nitrogen, favor colonization of roots by arbuscular mycorrhizal fungi (Klironomos et al. 1997). The relationship between elevated CO_2 and mycorrhizae is not well understood (Singer 1996), and there are conflicting reports on how it may be influenced by the nutrient status of the plant and soil. If a lower nitrogen status of plant tissue under increased CO_2 results in more mycorrhizal colonization, this could improve plant health through improved nutrient uptake. Similar confusion exists on the potential role of arbuscular mycorrhizal fungi and ectomycorrhizae in the suppression and biological control of plant pathogens. Mycorrhizae can have positive, negative, or neutral effects on plant disease, and their role is not well understood despite numerous studies on the subject (Pfleger and Linderman 1994). Clearly, the influence of mycorrhizae on plant health under climate change requires further research.

8.8.5 Quarantine and Exclusion

Management of climate change will put additional pressure on agencies responsible for exclusion as a plant disease control strategy (Kahn 1991). In some regions, certain diseases of economic concern do not currently occur because the climate has precluded the causal agents from becoming established. Use of geographical information systems and climate-matching tools may assist quarantine agencies in determining the threat posed by a given pathogen under current and future climates. This approach was used by Sansford and Baker (1998) to assess the risk of establishment of Karnal bunt in the cereal-growing regions of the European Union.

Exclusion of pathogens and quarantines through regulatory means may become more difficult for authorities as unexpected pathogens might appear more frequently on imported crops.

8.9 Impact Models

Quantitative (modeling) approaches, which allow one to investigate multiple scenarios and interactions simultaneously, will become more important for impact assessment (Coakley and Scherm 1996). Guidelines for such model-based assessments are needed, and Sutherst et al. (1996) and Teng and Yang (1993) have given a framework.

8.9.1 Climate Matching

Climate matching involves the calculation of a "match index" to quantify the similarity in climate between two or more locations. The match index is based on variables such as monthly minimum and maximum temperatures, precipitation, and evaporation. Software packages for climate matching include BIOCLIM (Busby 1991), HABITAT (Walker and Cocks 1991), or CLIMEX (Sutherst and Maywald 1985) and WORLD (Booth 1990). These packages often come with additional useful features such as internal algorithms for generating "climate surfaces" through interpolation between stations. Climate matching may be used for climate change impact assessment by identifying those locations on the globe with a current climate that is most similar to the predicted future climate at the location of interest. An analysis of the plant disease problems at the matching locations, for example, based on disease distribution maps (Weltzien 1972), would allow predictions to be made about future disease risk at the location of interest.

Booth et al. (2000) used climate matching to identify regions suitable for *Cylindrocladium* leaf blight on *Eucalyptus* spp. in Southeast Asia and around the world. They first established a simple rule for the presence or absence of the disease based on long-term means of temperature and precipitation. This rule was then implemented in a climate-matching program to identify high-risk regions in Africa, Australia, Latin America, and Southeast Asia under current climate. Further, two climate change scenarios were run for locations in Southeast Asia. The results suggested an increase in disease risk in Northern Vietnam, Southern Laos, and Eastern Thailand. These predictions are consistent with limited field observations indicating that severe disease can occur in these regions during years with extreme weather.

Possible effects of climate change on *Phytophthora cinnamomi*, a soilborne oomycete with an extremely wide host range, were considered by Brasier (1996) and Brasier and Scott (1994). This pathogen requires warm, wet soils and is hence limited primarily to tropical and subtropical regions (Lonsdale and Gibbs 1996). More recently, *P. cinnamomi* has been associated with oak declines in Southern and Mediterranean Europe. It was hypothesized (Brasier 1992) that this may be an early indication of climate warming as the pathogen may have become more active because of higher soil temperatures and/or increased host susceptibility caused by stress (e.g., more frequent winter droughts in the region). For a more formal impact assessment, Brasier and Scott (1994) used the CLIMEX climate-matching program (Sutherst and Maywald 1985) to map regions in Europe favorable or unfavorable for this pathogen under present and future climate scenarios. The climate change simulations suggested that the pathogen could extend its range further north, although it appeared unlikely that it could become established in those regions where winter temperatures are low such as Central and Eastern Europe (Brasier 1996). It was further hypothesized that the pathogen's host range could increase if spread occurs into regions where it is currently absent.

8.9.2 Empirical Models

Four diseases of two major crops in China, wheat and rice, were examined by regression analysis to determine how they have varied through time and whether this may relate to recent increases in mean and minimum temperatures (Yang et al. 1998). Rice blast and wheat scab have increased sharply since the 1970s. The wheat acreage infected with powdery mildew has become more extensive, whereas stripe rust has decreased steadily (Yang et al. 1998). This may be related to the increased spring and early summer temperatures and would be consistent with the changes in stripe rust observed in the Pacific Northwest associated with climate variability (Coakley et al. 1988).

Jahn et al. (1996) utilized long-term plant disease-monitoring records collected by the State Plant Protection Service in the former German Democratic Republic (GDR) to develop empirical climate–disease models for 15 individual host–pathogen combinations. These models were then used with various climate change scenarios to predict possible changes in "infestation levels" in a future climate. Calculations with the most realistic scenario (a temperature increase of 1 ± °C combined with a decrease in precipitation of 30 %) indicated that leaf rusts of wheat and barley and powdery mildew of sugar beet could increase substantially, reaching levels between two and five times as high as under the current climate. Infestation levels on small grains by powdery mildews would remain virtually unchanged, whereas those caused by foot rots and leaf blotch diseases would decrease. Most notable was a decrease in potato late blight to a mere 16 % of its current level. The authors cautioned against over-interpreting their results, which were based on calculations with data from only 1 of 14 regions in the former GDR.

8.9.3 Population Models

A very different conclusion regarding the importance of potato late blight under climate change was reached by Kaukoranta (1996). This author developed degree-day models for the emergence of potatoes and the date of late blight outbreaks in Finland. The two models were coupled and extended by including leaf area expansion of the crop as a function of thermal time, calculating radiation interception as a function of leaf area, transforming the intercepted radiation to tuber dry matter, and simulating the effects of late blight on tuber dry matter through a reduction in green leaf area, assuming that disease reduced leaf area to zero within 14 days after the predicted outbreak. Model parameters were obtained and model validation was done using data from a 3-year field and greenhouse study. The combined model was then used with various temperature change scenarios to predict possible changes in potato yield and yield losses caused by late blight in a warmer climate. The results suggested that tuber yield could increase by 2 t/ha per 1 ± °C warming in the absence of late blight. This potential yield gain was almost completely offset when late blight was considered, chiefly because late blight outbreaks occurred 4–7 days earlier and the period during which the crop was susceptible was lengthened by 10–20 days per 1 ± °C warming. This study did not consider possible yield-enhancing effects of elevated CO_2, nor did it incorporate the effects of changes in precipitation on late blight.

8.9.4 Simulation Models

Simulation models have been used extensively to predict yields of various crops in different agro-ecological zones under climate change (Riha et al. 1996). Biotic yield-reducing factors such as insects, pathogens, and weeds have, however, been largely ignored in these simulations (Teng et al. 1996). Because of this shortcoming, the development of linked disease–crop models is an important objective within the overall goal of developing a predictive capability for agricultural impact assessment and mitigation (Scherm 1999). For at least one key crop, rice, preliminary analyses considering the combined effects on yield of increased temperature, elevated UV-B radiation, and rice blast disease (*Pyricularia grisea*) have been done using a coupled simulation model (Luo et al. 1997). The model consisted of a physiological rice growth model and a leaf blast epidemic simulator, linked via the quantitative effects of leaf blast on photosynthesis and biomass production (Luo et al. 1997). Climate change was imposed by increasing mean temperature in fixed increments and by either including or omitting effects of UV-B on the host and pathogen (Luo et al. 1995). The results suggested that elevated UV-B could result in direct yield losses of 10 %. Impacts of increased temperature varied by agroecological zone, with an increase in blast and associated yield losses in cool, subtropical rice production regions (e.g., Japan) and a decrease in humid tropics and subtropical regions (e.g., the Philippines). The authors cautioned that the results must be considered preliminary as the simulations did not include neck and panicle blast, two other important symptom types caused by *P. grisea*. Further, increased CO_2 was not considered nor were changes in precipitation as preliminary analyses had indicated that the combined model was insensitive to changes in rainfall (Luo et al. 1995).

8.10 Adaptation and Mitigation

The climate is changing, resulting in changes in the plant diseases that we need to prevent or manage. Because climate change predictions are based on uncertain information, especially at regional and local levels, our response must be in the form of adaptive strategies that are reviewed and adjusted as new information and improved climate models become available. Developing effective strategies will require the involvement of government agencies, academia, and the general public.

Systematic quantitative analysis of climate change effects will be necessary for developing future disease management plans, such as plant breeding, altered planting date schedules, chemical and biological control methods, and increased monitoring of new disease threats. The existing preventive crop protection measures, such as use of diversity of crop species in the cropping systems, adjustment of sowing or planting dates, use of crop cultivars with superior resistance and/or tolerance to diseases and abiotic stress, use of reliable tools to forecast disease epidemics, application of IPM strategies, and effective quarantine systems, may become important in the future. Effective crop protection technologies are available and will provide appropriate tools to adapt to altered conditions. Therefore, real-time disease monitoring and surveillance have to be in priority to adopt measures against any unforeseen event that might happen due to climate change and/or global change as well as shifts in seasonality.

8.10.1 Enhanced Surveillance

Diagnostic tools and personnel are needed to detect new diseases. These newly introduced diseases can have devastating effects on plant communities. Increased surveillance by these and other agencies will be necessary if climate change results in more disease introductions.

8.10.2 Enhanced Research and Development

To date, little attention has been given to the effects of climate change on plant health. For plant diseases, the rapidity of the predicted climate change will necessitate more research into alternative crops and cultivars with increased stress tolerance and disease resistance, enhanced cultural practices, and climate-based site selection. Developing information and research networks will play a vital role by linking researchers and practitioners across the country to allow information to be gathered, reviewed, and redistributed to stakeholders.

8.10.3 Enhanced Public and Professional Awareness

Public awareness is increasing about the plant health hazards. Continuing education on climate-related disease issues would help plant disease scientists gain the skills to detect and identify newly emerging problems.

8.10.4 Integrated and Adaptive Policy Development

Mitigating and adapting to climate change will only be successful in a supportive and encouraging policy environment in many varied fields, including agriculture and natural resource management.

Under worst-case scenarios, several crops may require more fungicide spray treatments or higher application rates, thus increasing costs for farmers, prices for consumers, and the likelihood of the development of fungicide resistance (Juroszek and von Tiedemann 2011). Some agricultural systems may be more flexible than others in the adoption of new cultivars and cultural practices to cope with the increased risk of certain diseases. Annual crops will have an advantage over perennials, as they provide more flexibility when it comes to adopting new cultivars and cultural practices. Potential adaptation strategies must be accompanied by cost–benefit analyses. Evaluating the efficacy of current physical, chemical, and biological control methods under changing climatic conditions and research concerning new tools and strategies (including plant breeding) for coping with the predicted changes will be of great strategic importance.

Fungicides may continue to serve as common disease suppression agents, although alternative measures, such as cultural methods and biological control, should be developed.

The persistence of crop protection chemicals in the phyllosphere is highly dependent on weather conditions. Changes in duration, intensity, and frequency of precipitation events will affect the efficacy of chemical pesticides and how quickly the active molecules are washed away. Temperature can directly influence the degradation of chemicals and alter plant physiology and morphology, indirectly affecting the penetration, translocation, persistence, and modes of action of many systemic fungicides (Coakley et al. 1999).

Plant diseases are a major problem not only for food production but also for the quality and safety of important food stuffs. In Europe, mycotoxins and pesticide residues are among the top food safety concerns associated with a changing climate. For example, the concentration of mycotoxin produced by Fusarium head blight in grain generally increases with the number of rainy days and days with high RH but decreases with low and high temperatures. Changes in both temperature conditions and atmospheric composition may influence the severity of outbreaks of Fusarium head blight and the production of mycotoxins. The most significant effects of mycotoxin presence generally occur during the production phase, but the entire wheat value chain can be affected (Chakraborty and Newton 2011). Shifts in any of the components of the disease triangle can dramatically affect the magnitude of disease expression in a given pathosystem. Therefore, it is not at all surprising that disease patterns have already changed and will continue to change in response to the effects of climatic changes on pathogens and hosts. The ultimate solution for crop adjustment to climate change is breeding for desired characteristics associated with future needs. Breeding programs for crop plants and forest trees can promote genetic diversity, disease resistance, and tolerance of environmental stresses. These breeding goals should, of course, be coupled with traditional breeding goals, such as yield, quality, and proper shelf-life.

Indigenous microbial communities play an important role in maintaining plant health. There is a need to promote these beneficial communities. Recent technological advances, such as metagenomic analyses, will increase our understanding of microbial dynamics in soil and other environments and further advance the establishment of plant-pathogen suppressive microbial populations. One adaptation measure that can be imagined is the introduction of beneficial microorganisms (biocontrol agents) to plant surfaces, so that this niche can be occupied in a way that tilts the plant–microorganism interaction in a healthy direction. Among the beneficial microorganisms that have been examined, there are some that have been found to persist in stressful microclimates. The selection of such microorganisms and the development of formulations for agricultural use may help growers cope with both abiotic and biotic plant stresses.

It is not advisable to depend on one “high input variety” or one breed of crop variety. Varieties should be mixed and changed. A broad genetic variability serves as a foundation for robust crops. In addition, it seems more recent traditional breeding has not selected for CO_2

responsiveness, which simply means newer breeds do not benefit from elevated CO_2 as much as older breeds (Ainsworth et al. 2008). The simple agronomic measures such as mixing varieties reduced rice blast severity by 94 % and increased yield by 89 %.

Following crop rotation increases biodiversity. Crop residues are often host of pathogens and alternating crops will prevent the infection from the residues to the host crop.

Ecologically based pest management (EBPM) considers belowground and aboveground habitat management equally important. A "healthy" soil, with optimal physical, chemical, biological properties, increases plant resistance to diseases (Altieri et al. 2005). Excess of nitrogen can increase the severity of certain diseases.

8.10.5 Transgenic Disease-Resistant Varieties

Transgenic ring spot virus-resistant papaya has been genetically engineered to contain a virus gene that encodes for the production of the coat protein of the virus. As a major component of viruses, the coat protein's primary function is to protect viral genetic information. Expression of this gene in the resulting papaya line renders the plants resistant to the virus (Fig. 8.5).

The transgenic plum called C5 (variety Honey Sweet) expresses a plum pox virus coat protein, the plant produces the coat protein mRNA, and it is processed by a system called posttranscriptional gene silencing (PTGS), which functions like the plant's immune system and is mechanistically similar to RNAi (Hily et al. 2004). C5 provides a unique source of germplasm for future breeding programs worldwide (Fig. 8.6).

Approaches that have been used to produce transgenic sweet potato include expression of viral replicase genes, anti-sense RNAs, and viral coat protein genes. Transgenic sweet potato is resistant to feathery mottle virus (FMV) and has the potential of increasing yields of sweet potato roots and foliage.

Exploitation of the plant immune system against cassava mosaic disease by expression of hairpin RNA homologous to viral sequences has proven effective to generate virus-resistant cassava (Yadav et al. 2011).

Fig. 8.5 Yellow plants on the *left* are nontransgenic papaya severely infected with ringspot virus; plants on *right* are transgenic 'Rainbow' papaya resistant to ringspot virus

Specifically in summer squash, coat protein-mediated resistance is used against viruses. Transgenic summer squash plants (CZW3, Liberator III, and Destiny III) with resistance to three viruses (cucumber mosaic virus, zucchini yellow mosaic virus, and watermelon mosaic virus 2) produce as many or more marketable fruit than nontransgenic squash. A Cornell University study found that transgenic squash with resistance to three viruses produced a 50-fold increase in marketable yield over nontransgenic varieties (Fuchs et al. 1998).

The GM potato variety Desiree has been transformed with an R or resistance gene (Rpi-vnt1.1) along with its native promoter and terminator intact, using GMO technology. The R-gene confers the GM potato line with resistance to the late blight fungus.

The RNA interference (RNAi) gene was introduced in pinto bean (*Phaseolus vulgaris*). This GM bean is resistant to the golden mosaic virus.

Fig. 8.6 *Left* – C5 (variety Honey Sweet) genetically modified plum resistant to plum pox virus. *Right* – severe symptoms of plum pox virus (PPV) infection on susceptible plum fruits

The transgenic bean could increase production by 10–20 %.

The coat protein (CP) gene of cucumber mosaic virus (CMV) was cloned into sweet pepper plants to confer resistance to CMV.

Transgenic rice lines with inducible production of ethylene (ET) were generated by expressing the rice ACS2 (1-aminocyclopropane-1-carboxylic acid synthase, a key enzyme of ET biosynthesis) transgene under control of a strong pathogen-inducible promoter. The transgenic lines exhibited increased resistance to a field isolate of sheath blight (*Rhizoctonia solani*) as well as different races of blast (*Magnaporthe oryzae*).

Commercially available genetically modified crops for disease resistance are presented in Table 8.4 (Castle et al. 2006).

8.11 Future Prospects

As a discipline, plant pathology is dedicated to ensuring sustainable production in agricultural systems through the management and improvement of plant health. In the foreseeable future, global climate change will impact on plant health and its management to influence productivity. The role of plant pathologist must be to provide an assessment of how plant diseases will impact on agricultural systems under climate change in order to minimize loss to production and quality. Outcomes from this research will have important implications for decisions on amelioration and mitigation strategies. Due to uncertainties in climate change predictions (IPCC 1996), a “no regrets approach,” where the proposed actions have definite and quantifiable benefits, with or without the effects of climate change factored in, should provide the rationale for this research. An example would be an improved understanding of a disease cycle; this will enhance our capacity to predict and manage the disease under current climatic conditions in addition to improving our capacity to respond to climate change.

Climate change may have positive, negative, or neutral impact on diseases. Research in this area is as much about identifying new opportunities as preparing to minimize negative impacts. Success will require an improved understanding of the causes, impacts, and consequences of climate change from which will evolve amelioration and mitigation strategies. The shortage of critical epidemiological data on individual plant diseases needs to be addressed using experimental approaches. In the first instance, studies in a controlled environment may be used to formulate

Table 8.4 Commercially available genetically modified crops for disease resistance (Castle et al. 2006)

Crop	Trait phenotype	Target trait gene(s)	Trait designation	Originating company	Year of first commercial sale	Trade name
Squash	Resistance[a] to CMV, WMV2, and ZYMV	Coat protein genes of CMV, WMV2, and ZYMV	CZW3	Asgrow; Seminis Vegetable Seeds (now Monsanto)	1998	Destiny III, Conqueror III, Liberator III
	Resistance[a] to WMV2 and ZYMV	Coat protein genes of WMV2 and ZYMV	ZW-20	Asgrow; Seminis Vegetable Seeds (now Monsanto)	1995	Preclude II, Patriot II, Declaration II, Independence II
Papaya	Resistance[a] to PRSV	Coat protein gene of PRSV	55-1 63-1	Cornell university; University of Hawaii, USDA	1998	SunUp, Rainbow

[a] *CMV* cucumber mosaic virus, *PRSV* papaya ring spot virus, *WMV2* watermelon mosaic virus, *ZYMV* zucchini yellow mosaic virus

hypotheses and to determine critical relationships to help develop process-based approaches. Field-based research examining the influence of a combination of interacting factors (Norby et al. 1997) would be needed to provide a more realistic appraisal of impacts. Methodology to model climate change impact has not been fully developed. Some of the impact assessments (Brasier and Scott 1994) are "first pass analysis" using climate-matching software such as BIOCLIM (Busby 1991), HABITAT (Walker and Cocks 1991), or CLIMEX (Sutherst and Maywald 1985). Some have used and advocated the use of simulation models (Luo et al. 1995; Teng et al. 1996). However, their use is currently limited due to a lack of hard data on impacts. Empirical procedures for assessing long-term climate and disease interactions are only just beginning to emerge (Scherm and Yang 1995; Coakley and Scherm 1996). There is a need to look beyond the science of plant pathology to seek and invite concepts and ideas from other relevant disciplines for a reappraisal of priorities. Developments in information technology can help in the quest for knowledge and its dissemination (Bridge et al. 1998).

Knowledge needs to be acquired, synthesized, and generalized at a scale relevant to an environmental unit. Impact on an agricultural system must include on- and off-farm effects determined at a landscape scale of spatial resolution. Historically plant pathology research using site-specific knowledge of individual pathosystems has served well in understanding, predicting, and managing diseases. Environmental variables at the microclimate level have been utilized at this spatial scale. In contrast, climate systems operate at a global scale, and general circulation models (GCMs) are better at explaining climate at this coarse level of resolution. This difference in the level of understanding between plant pathology and biometeorology/climatology at the various spatial and temporal scales has hampered interdisciplinary interaction. The need to bridge this gap in knowledge has been recognized (Kennedy 1997). In recent years, a number of attempts have been made to downscale GCM outputs to a biologically relevant mesoscale (Bardossy 1997). Lack of epidemiologically relevant weather variables has been an impediment to the application of GCMs and other climate models to plant disease modeling. Duration of surface wetness and relative humidity, which critically influence infection and disease development by many plant pathogens, have not been easily obtained from GCM output until recently. Usefulness of remotely gathered site-specific wetness and other data for plant pathology research has been variable (Gleason et al. 1997), and Seem et al. (2000) provide a more detailed discussion on this topic.

8.12 Research Needs

Research needs to be undertaken on the following lines:

- Better understanding of gene expression in plants and pathogens in response to climatic factors
- Integrated omic studies of host and pathogen responses, as well as communities of soil- and plant-associated microbes
- Multifactor studies of climate change effects
- Better models of adaptation rates
- Better data and models related to dispersal, current levels of intraspecific diversity, strength of selection under different climate change scenarios, and heritability of traits
- Long-term large-scale records of pathogen and host distributions
- Models of regional processes that incorporate disease
- Data and models describing dispersal of propagules and vectors
- Integrated multidisciplinary international networks for data collection and synthesis

8.13 Conclusions

Climate change can have positive, negative, or neutral impact on individual pathosystems because of the specific nature of the interactions of host and pathogen. As a result, it has been difficult to decipher rules of thumb that may be used for specific impact assessment. Three factors are largely responsible for this apparent lack of general principles. First is a serious lack of knowledge of the effects of some important factors such as CO_2. The role of pathogens in the response of plants to increased CO_2 has not been well studied; hence, its effect on disease is not currently considered in crop simulation models. Second, there is only rudimentary information on the interactions of individual factors that collectively influence plant disease in a changing climate. For example, recent studies showed that the impacts of ozone in the field cannot be estimated without considering the predisposing effects of fungal infections and the compensating effects derived from elevated CO_2 (von Tiedemann and Firsching 2000). Third, impacts on plant disease have largely been considered in small-scale experiments. Given that climate change operates at a global scale, a lack of understanding of epidemic processes at relevant environmental and spatial scales has hampered progress. The uncertainties associated with climate change projections and the difficulty in extracting epidemiologically meaningful environmental variables such as surface wetness from GCMs have contributed to this.

From a disease management viewpoint, information is generally required for a specific disease at a field scale; hence, data on potential impacts of climate change need to be assessed and evaluated at a detailed level to capture important mechanisms and dynamics that drive epidemics. In the absence of climate change considerations, existing site-specific knowledge of individual pathosystems, often incorporating environmental variables at the microclimate level, serves well to understand and manage disease. When climate change considerations are included, deficiencies arise because of a lack of detailed knowledge of epidemiology and the relevant meteorological variables needed to predict epidemics at this spatial scale. Ideally, the necessary epidemiological data would be gathered from long-term field studies in facilities where more than one climate change variable can be examined (Norby et al. 1997). As for meteorological data, statistical downscaling of GCM output offers interesting opportunities for developing climate change predictions for small-scale spatial units such as a farm (Seem et al. 1999).

Information is also required by planners and policymakers at a much broader spatial scale such as a region, state, or country. Climate matching and similar models are not based on mechanisms or dynamics that drive epidemics; nevertheless, these approaches are useful as first pass analyses and to develop integrated assessment models that incorporate socioeconomic aspects (Sutherst et al. 1996). If measures of uncertainty are included (Scherm 2000), output from GCMs is well suited for impact assessment at these coarse levels of resolution. Data on pathosystems would have to be acquired and synthesized at this scale to include both on- and off-farm effects of disease and other production constraints for a realistic appraisal of crop loss.

If changes in atmospheric composition and global climate continue in the future as predicted, there will be relocation of crops, and their diseases and impacts will be felt in economic terms from crop loss. Changes in levels of CO_2, ozone, and UV-B will influence disease by modifying host physiology and resistance. In addition, changes in temperature, precipitation, and the frequency of extreme events will influence disease epidemiology. Changes in geographical distribution will potentially alter the relative importance and spectrum of diseases, and new disease complexes may arise. Evolution of pathogen populations may accelerate from enhanced UV-B radiation and/or increased fecundity in elevated CO_2. As a result, host resistances may be overcome more rapidly. Disease management will be influenced due to altered efficacy of biological and chemical control options. Information gathered so far has been fragmented, and a comprehensive analysis of climate change impacts on diseases is not possible with present knowledge. Experimental research on a diverse range of disease systems is necessary to improve comprehension of climate change impacts. There is a need to strengthen modeling approaches to impact assessment, given the multitude of atmospheric and climatic factors, possible change scenarios, and the number of disease systems. For instance, changes in both mean temperature and its variability are equally important in predicting the potential impact of climate change (Scherm and van Bruggen 1994). Given that climate change is a global issue, the focus needs to shift from paddock-based assessment on specific diseases to a more ecologically relevant spatial unit (Scherm et al. 2000) to consider climate with other associated changes in land use and vegetation cover (Luo et al. 1995), among others.

Apart from the technical difficulties listed above, the most significant limitation to climate change impact assessment is our inability to predict how technological and socioeconomic forces will interact with atmospheric, climatic, and biological factors to shape the agriculture of the twenty-first century. Technological progress over the next 50 years will doubtless revolutionize crop production and animal husbandry. Hence, even in the absence of climate change, it would be a daunting task to predict future agricultural production potential. For example, how will land-use patterns change in response to market demands, technology, and accelerated population growth? To what degree will transgenic technology be able to alleviate crop stresses caused by drought, nutrient limitations, and pests? Will crop protection chemicals still be available to control insects, diseases, and weeds? Compared with these changes, the prospect of climate change seems a minor concern indeed. Nevertheless, climate change and climate variability add another layer of complexity and uncertainty onto a system that is already exceedingly difficult to manage. Better understanding of how these forces interact with biological yield constraints such as plant pathogens will therefore contribute appreciably to the development of sustainable agricultural systems.

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Impacts on Nematode Pests

9

Abstract

Plant pathogenic nematodes are one of the important biotic constraints in crop production. Climate change due to increased emission of greenhouse gases is posing a serious challenge to sustainability of crop production by interfering with biotic and abiotic components and their interactions with each other. Global warming resulting in elevated carbon dioxide (CO_2) and temperature in the atmosphere may influence plant pathogenic nematodes directly by interfering with their developmental rate and survival strategies and indirectly by altering host plant physiology. Available information on effect of global warming on plant pathogenic nematodes though limited indicates that nematodes show a neutral or positive response to CO_2 enrichment effects with some species showing the potential to build up rapidly and interfere with plant's response to global warming. Studies have also demonstrated that the geographical distribution range of plant pathogenic nematodes may expand with global warming spreading nematode problems to newer areas. Besides plant parasites, other trophic groups (microbial feeders, predators, and insect parasites) of soil nematodes also shown to influence the plant productivity indirectly by regulating the key ecosystem processes including decomposition, nutrient mineralization, biological pest suppression, and energy transfer in food webs. These findings underline the importance of understanding the impact of climate change on soil nematodes and its implications to crop production while developing mitigation and adaptation strategies to address impact of climate change on agriculture.

Keywords

Nematodes • Climate change • Global warming • Agriculture • Geographical distribution • Pest management

Soil nematodes are very small (0.3–5.0 mm long as adults) worm-like animals which occur in millions per square meter of soil. Nematodes are ubiquitous and the most abundant group of multicellular organisms on earth (Sohlenius 1980). They are represented at more than one trophic level in soil food web as they act as primary consumers (herbivores), secondary consumers

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(bacterivores and fungivores), and tertiary consumers (omnivores, carnivores, and predaceous nematodes) (Yeates et al. 1993). Nematodes play multiple and contrasting (positive and negative) roles in regulating productivity of plant- and animal-based production systems.

Nematodes feed on a wide range of soil organisms (bacteria, fungi, slug eggs, insect larvae) as well as plant roots. Herbivorous nematodes can cause crop losses especially in root crops like potatoes and beets grown mostly in Europe, but also in soybean grown in Asia (IPCC 2007). Many nematode species work as natural enemies of insect larvae and slugs.

Herbivore nematodes feed on plant parts mostly on roots. It is estimated that nematodes cause crop losses worth US$ 125 billion annually in agriculture (Chitwood 2003). Bacterial and fungal feeding nematodes are beneficial to crop growth because they help in enhancing the nutrient availability to crop plants. Predatory nematodes predate on plant-parasitic nematodes and thus have potential for biocontrol. Insect parasitic or entomopathogenic nematodes are beneficial to crop production as they help in biocontrol of insect pests of crop plants and in reducing the consumption of chemical pesticides (Grewal et al. 2005). Animal parasitic nematodes whose free-living stages also occur in soil adversely affect the productivity of livestock and health of agricultural workers. By virtue of their trophic diversity, they form an important energy pathway from primary production and detritus to higher trophic groups. Therefore, they constitute a fundamental group of biological indicators that needs to be investigated from the perspective of climate change impacts.

9.1 Crop Losses

On a worldwide basis, the ten most important genera of plant-parasitic nematodes were reported to be as follows (Sasser and Freckman 1987):

Meloidogyne	*Rotylenchulus*
Pratylenchus	*Helicotylenchus*
Heterodera	*Tylenchulus*
Ditylenchus	*Xiphinema*
Globodera	*Radopholus*

The estimated overall average annual yield loss of the world's major crops due to damage by plant-parasitic nematodes is 12.3 % (Table 9.1). For the 20 crops (left-hand column) that stand between man and starvation (life-sustaining horticultural crops), an estimated annual yield loss of 10.7 % is reported. The 20 crops (right-hand column) that represent a miscellaneous group important for food or export value were reported to have an estimated annual yield loss of 14 %.

Monetary losses due to nematodes on 21 crops, 15 of which are life sustaining, were estimated at US$ 77 billion annually based on 1984 production figures and prices.

These figures are staggering, and the real figure, when all crops are considered, probably

Table 9.1 Estimated annual yield losses due to damage by plant-parasitic nematodes – World basis (Sasser and Freckman 1987)

Life-sustaining crops	Loss (%)	Economically important horticultural crops	Loss (%)
Banana	19.7	Cocoa	10.5
Barley	6.3	Citrus	14.2
Cassava	8.4	Coffee	15.0
Chickpea	13.7	Cotton	10.7
Coconut	17.1	Cowpea	15.1
Corn	10.2	Eggplant	16.9
Field bean	10.9	Forages	8.2
Millet	11.8	Grapes	12.5
Oat	4.2	Guava	10.8
Peanut	12.0	Melons	13.8
Pigeon pea	13.2	Misc. other	17.3
Potato	12.2	Okra	20.4
Rice	10.0	Ornamentals	11.1
Rye	3.3	Papaya	15.1
Sorghum	6.9	Pepper	12.2
Soybean	10.6	Pineapple	14.9
Sugar beet	10.9	Tea	8.2
Sugarcane	15.3	Tobacco	14.7
Sweet potato	10.2	Tomato	20.6
Wheat	7.0	Yam	17.7
Average	**10.7 %**	**Average**	**14.0 %**
Overall average – 12.3 %			

exceeds US$ 100 billion annually. The losses are 5.8 % greater in developing countries than in developed countries (Sasser and Freckman 1987).

9.2 Climate Change and Nematodes

Soil nematodes are dependent on the continuity of soil water films for movement. Their activities are largely controlled by soil biological and physical conditions (Yeates and Bongers 1999).

Scientific research on climate change and its impact on herbivorous nematodes are very limited. However, based upon their environmental requirements, some assumptions are possible. Severe droughts resulting in a reduction of soil water will most likely negatively affect soil nematodes. Higher average temperatures will probably have little effect, since thermal conductivity of soils is low.

Apparently, a prediction of how climate change will affect herbivorous soil nematodes and thus yields cannot be made. There is some evidence that population dynamics may change, but so far no trend is clear. Basically, and most likely true for all ecological research, the impacts of climate change are specific to crop/plant, region, and interacting species.

The majority of plant pathogenic nematodes spend part of their lives in soil, and therefore, soil is the source of primary inoculum. Life cycle of a nematode can be completed within 2–4 weeks under optimum environmental conditions. Temperature is the most important factor, and development is slower with cooler soil temperatures. Warmer soil temperatures are expected to accelerate nematode development, perhaps resulting in additional generations per season, and drier temperatures are expected to increase symptoms of water stress in plants infected with nematodes such as the soybean cyst nematode. Overwintering of nematodes is not expected to be significantly affected by changes in climate, although for some, such as the soybean cyst nematode, egg viability may be reduced in mild winters.

Plant pathogenic nematodes are one of the important biotic constraints in crop production. Climate change due to increased emission of greenhouse gases is posing a serious challenge to sustainability of crop production by interfering with biotic and abiotic components and their interactions with each other. Global warming resulting in elevated carbon dioxide (CO_2) and temperature in the atmosphere may influence plant pathogenic nematodes directly by interfering with their developmental rate and survival strategies and indirectly by altering host plant physiology. Available information on effect of global warming on plant pathogenic nematodes though limited indicates that nematodes show a neutral or positive response to CO_2 enrichment effects with some species showing the potential to build up rapidly and interfere with plant's response to global warming. Studies have also demonstrated that the geographical distribution range of plant pathogenic nematodes may expand with global warming spreading nematode problems to newer areas. Besides plant parasites, other trophic groups (microbial feeders, predators, and insect parasites) of soil nematodes also have shown to influence the plant productivity indirectly by regulating the key ecosystem processes including decomposition, nutrient mineralization, biological pest suppression, and energy transfer in food webs. These findings underline the importance of understanding the impact of climate change on soil nematodes and its implications to crop production while developing mitigation and adaptation strategies to address impact of climate change on agriculture.

Nematodes by virtue of their trophic diversity occupy a central position in soil food webs and play an important role in providing vital ecosystem services. Acting directly as pests and indirectly as vectors of other plant pathogens and consumers of microflora and fauna, nematodes play a significant role in regulating plant growth, biological pest suppression, and nutrient cycling in agroecosystems.

9.3 CO_2 Enrichment

CO_2 concentration plays a crucial role in various aspects – biology of plant and insect parasitic nematodes including host recognition, recovery from dauer stage or diapause, etc. Elevated CO_2 levels may also influence these nematodes indirectly by altering host physiology (defense mechanisms such as production of secondary metabolites and nutrient status such as C:N ratio). It may also influence microbial feeding nematodes due to changes in quality and availability of food under enriched CO_2 conditions in soil. The impacts of climate change can be positive, negative, or neutral, since these changes can decrease, increase, or have no impact on nematode abundance, depending on each region or period.

Available information on effect of global warming on soil nematodes though limited indicates that abundance of soil nematodes in general is either increased or unaffected by elevated CO_2 levels, while individual species and trophic groups differ considerably in their response to climate change. Herbivorous nematodes showed neutral or positive response to CO_2 enrichment effects with some species showing the potential to build up rapidly and interfere with plant's response to global warming.

Similar to other organisms which feed on plants, increased CO_2 levels are believed to have an impact on herbivorous nematodes (Ayres et al. 2008), and several studies have been conducted, where the aboveground plant community was exposed to elevated CO_2. Almost all of these studies were done in different grasslands and forests, and thus results have been variable and contradictory. Research results regarding nematodes, from experiments conducted on agricultural crops in arable soils, are very limited. Basically, all kinds of results were determined: increase, decrease, and no change of nematode populations (Sticht et al. 2009). A recent publication presents results of a long-term agricultural experiment conducted in winter wheat and sugar beets in Germany. Winter wheat and sugar beet were grown in rotation under 550 ppm atmospheric CO_2 compared to ambient (380 ppm) atmospheric CO_2. The number of herbivore, bacterivore, and fungivore nematodes was significantly higher under wheat and sugar beets grown under elevated CO_2, while the number of carnivore was not changed. The total numbers of herbivore, bacterivore, and fungivore nematodes were higher under elevated CO_2 wheat than under elevated CO_2 sugar beet, most likely due to the very different root system of both plant species (Sticht et al. 2009). However, impacts on yield were not determined.

The observations that elevated CO_2 levels often induce increased root production. It can be presumed that herbivorous nematode communities will be relatively more affected by increases in atmospheric CO_2 concentration. Positive effects of CO_2 enrichment on the abundance of herbivorous nematodes have been reported in some studies (Yeates et al. 2003). The abundance of *Tylenchus* and *Longidorus* increased after 5 years of CO_2 enrichment, but there was no effect on the abundance of *Paratylenchus*, *Trichodorus*, and members of Hoplolaimidae in pasture plots (Yeates et al. 2003). Yeates et al. (1997) reported increase in abundance of *Meloidogyne* in response to CO_2 enrichment in grassland turfs while 7 other herbivorous nematode taxa were not affected. The abundance of *Pratylenchus* was positively associated with CO_2 concentration in gley, but not in organic soil around a natural CO_2 vent in New Zealand (Yeates et al. 1999).

Although root biomass increased under elevated CO_2, the damage due to root-feeding nematodes was more under elevated CO_2 compared to the ambient levels in a grass species (Wilsey 2001). Similarly, neutral responses of herbivorous nematodes to CO_2 enrichment were observed despite increase in root production by 3–32 % in different locations (Ayres et al. 2008). This may be due to decrease in root quality (low nitrogen content) or increase in nematode antagonists.

The interaction of elevated CO_2 with nitrogen fertilization or residue addition significantly affected the soil nematode community indices. The residue addition stimulated structure index and inhibited plant-parasite response to the elevated CO_2 in a wheat field (Li et al. 2009).

Experiments with rice have showed no adverse effects of elevated CO_2 levels up to 700 ppm on the abundance of soil nematodes and penetration

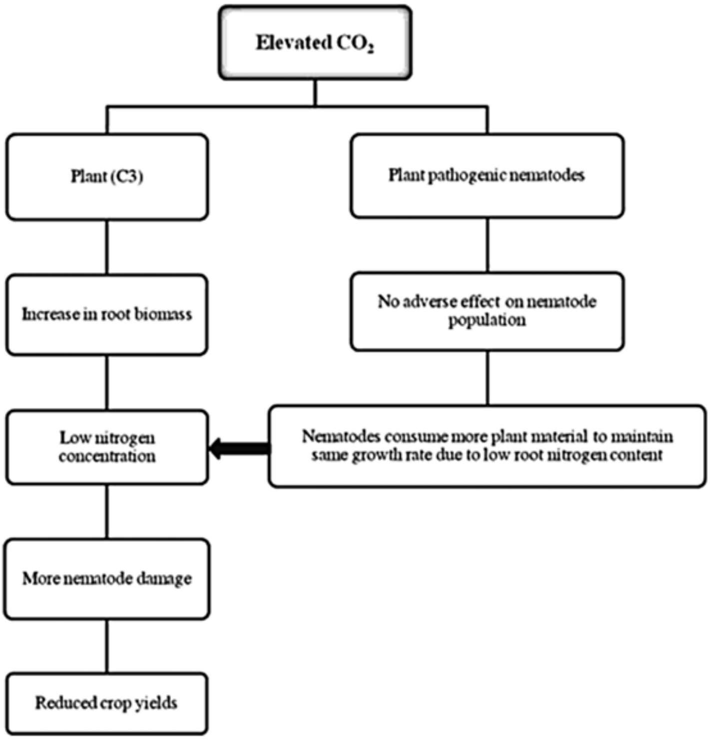

Fig. 9.1 Consequences of elevated CO_2 levels on plant–nematode interaction and crop productivity (Somasekhar and Prasad 2012)

of rice root-knot nematode, *M. graminicola* (Fig. 9.1) (Somasekhar and Prasad 2010).

Critical assessment of available information on responses of herbivorous nematodes to CO_2 enrichment reported from different ecosystems indicates that the responses are either neutral or positive but not negative so far (Table 9.2).

9.4 Elevated Temperatures

Temperature is the most important environmental factors that affect plant response to nematodes. It affects nematode survival, distribution, embryogenesis and hatching, migration and penetration, development, and symptom expression in the plants. Temperature requirements vary among root-knot nematode populations (thermotypes) and with each host-parasite combination. Non-efficient hosts of root-knot nematodes become progressively efficient as temperature rises. The fact that plants become efficient hosts at high temperatures is probably due to three factors:

- High temperatures are optimum conditions for nematode activity.
- Stress caused by high temperature makes the plants more vulnerable to nematode attack.
- Chemicals responsible for cell necrosis may not be produced or may be neutralized or counteracted at high temperature.

Temperature is the most important factor influencing the biology of nematodes. Nematode developmental rate is directly influenced by the temperature with slower development at cooler and faster growth rate at warmer soil temperatures. In plants under environmental stress (at high temperatures), nematode reproduction is higher. Hatching and embryogenesis is faster, and migration and penetration by the nematode is favored by high temperatures. The nematode life cycle is also completed faster at high temperature; therefore, more generations are produced. Moreover, at high temperatures, fewer males develop. Therefore, increase in atmospheric temperature due to global warming is expected to result in more number of generations per season and expansion of their geographical distribution

Table 9.2 Response of herbivorous nematodes to CO_2 enrichment

Location	Cropping system	Experimental arena[a]	Nematode response[b]	References
New Zealand	Grassland	CER	+/N	Yeates et al. (1997)
New Zealand	Grassland	Vent	N	Yeates et al. (1999)
New Zealand	Grassland	FACE	+/N	Yeates et al. (2003)
California, USA	Grassland	OTC	+/N	Hungate et al. (2000)
California, USA	Grassland	OTC	N	Ayres et al. (2008)
California, USA	Grassland	OTC	N	Ayres et al. (2008)
Germany	Grassland	FACE	+/N	Sonnemann and Wolters (2005)
Germany	Sugar beet and wheat rotation	FACE	+	Sticht et al. (2009)
Switzerland	Grassland	SACC	N	Niklaus et al. (2003)
Montpellier, France	Grassland	CER	N	Ayres et al. (2008)
China	Rice–wheat rotation	FACE	+/N	Li et al. (2007, 2009)
India	Rice	OTC	N	Somasekhar and Prasad (2010)

[a] *OTC* Open top chambers, *SACC* screen-aided CO_2 control, *FACE* free air CO_2 enrichment, *CER* controlled environment room, *Vent* natural CO_2 vent

[b] + Positive or increase in abundance, *N* neutral or not affected

range. Other potential effects of elevated temperature on parasitic nematodes include altered sex ratio, host defense responses, and interference in their survival strategies like dauer juveniles or egg diapauses in extreme environments.

Drier temperatures are expected to increase symptoms of water stress in plants infected with nematodes such as the soybean cyst nematode. Overwintering of nematodes is not expected to be significantly affected by changes in climate, although for some, such as the soybean cyst nematode, egg viability may be reduced in mild winters.

Plantain (*Musa* spp. AAB) is both an important staple and cash crop throughout the West/Central African humid forest zone. Major yield constraints are root nematodes, particularly *Radopholus similis*. Data from lab and field experiments demonstrate higher nematode population densities and greater plantain root damage at the projected temperature increases. *R. similis*, currently absent from cooler, higher altitude areas, is likely to expand its range.

Climate change may also influence the plant nematode interactions by interfering with host defense mechanisms. Rebetez and Dobbertin (2004) reported that strong climate warming that has occurred in recent years favored pine wood nematode (*Bursaphelenchus mucronatus*) and bark beetles and increased drought stress reduced tree resistance against these pests. This resulted in rapid tree mortality in pine forests in Switzerland.

9.4.1 Breakdown of Nematode Resistance

Genetic resistance to *Meloidogyne* spp. is sensitive to soil temperatures above 28 °C. Tomato, bean, and sweet potato lose resistance at elevated soil temperatures (Dropkin 1969; Fassuliotis et al. 1970; Jatala and Russell 1972). High soil temperatures appear to be the main reason that root-knot nematode resistance is not effective in Florida, USA (Walter 1967), and in many tropical countries. Results by Araujo et al. (1983) indicate that race 4 of *M. incognita* reproduces better on resistant tomato genotypes than on race 1.

The resistance to root-knot nematode in tomato (cv. ‘Sanibel’) has often failed as a result of the heat instability or apparent temperature sensitivity of the resistant Mi gene (Fig. 9.2). For example, previous research has demonstrated threshold soil temperatures and incremental reductions in nematode resistance with each degree above 78 °F, such that at 91 °F tomato plants are fully susceptible. This would suggest that in Florida, use of these varieties may have to be restricted to spring plantings when cooler soil temperatures prevail.

In bell pepper, two newly developed root-knot nematode-resistant varieties (Charleston Belle and Carolina Wonder) confer a high degree of resistance to the root-knot nematode; however, expression of resistance is heat sensitive. Further research is necessary to characterize the usefulness of these varieties under the high soil temperature conditions of Florida. Like tomato, use of these varieties may have to be restricted to spring plantings when cooler soil temperatures prevail.

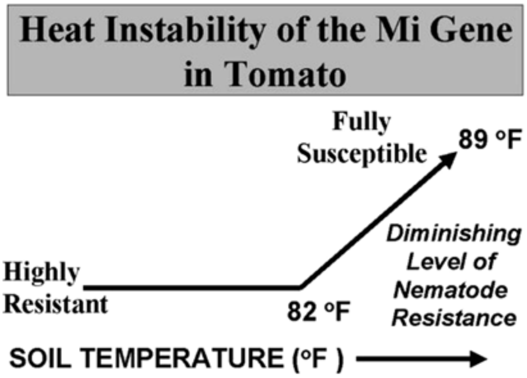

Fig. 9.2 Diagrammatic representation showing the complete loss of root-knot nematode resistance conferred by the Mi gene in tomato with increasing soil temperature

Susceptibility of bell pepper (Charleston Belle, Carolina Wonder, Keystone Resistant Giant, and Yolo Wonder B) to *M. incognita* increased as temperature increased from 24 to 32 °C. Reproduction factor of *M. incognita* and root galling increased ($P<0.05$) for all cultivars as temperature increased (Table 9.3). Overall, reproduction of *M. incognita* and severity of root galling on the resistant isolines Charleston Belle and Carolina Wonder were less ($P<0.05$) than on susceptible Keystone Resistant Giant and Yolo Wonder B, and the two cultivars within each group did not differ. However, temperature x cultivar interaction was found ($P<0.05$) for reproduction index and root galling (Thies and Fery 1998).

In grapevine, the number of galls and egg sacs of *M. javanica* increased with time and temperature on both rootstocks, although not significantly in all cases (Table 9.4). This increasing infestation with time can be ascribed to normal population increase with increasing degree days (Loubser 1988). Furthermore, pathogenicity as measured by the degree of galling also appeared to increase with increasing temperature. This was more evident on the moderately resistant rootstock 143 B Mgt (*Vitis vinifera* x *V. riparia*) [compared to the susceptible rootstock Jacquez (*Vitis aestivalis* x *V. cinerea* x *V. vinifera*)] where the number of eggs increased significantly (and galling apparently also) between treatments B and C, irrespective of the number of degree days which remained the same. The reason for this was seen as a breakdown in resistance at the

Table 9.3 Comparison of four bell pepper cultivars differing in resistance to southern root-knot nematode grown at 24, 28, or 32 °C on reproductive index and root galling 8 weeks after inoculation with *Meloidogyne incognita*

	Reproductive index^{x}			Gall index^{y}		
Temperature/cultivar	24 °C	28 °C	32 °C	24 °C	28 °C	32 °C
Charleston Belle	0.3 a^{z}	4.9 b	24.7 c	1.53 a	2.46 b	3.61 c
Keystone Resist. Giant	6.1 c	32.2 de	29.9 f	4.79 d	7.62 e	8.74 f
Carolina Wonder	0.1 a	4.0 b	22.9 c	1.57 ab	2.37 ab	3.55 c
Yolo Wonder B	4.7 c	29.4 de	125.8 ef	4.37 cd	7.82 ef	8.61 ef

^{x}Reproduction index (final population/initial population) of *M. incognita*

^{y}Gall index: 1 = no galls, 2 = 1–3 %, 3 = 4–16 %, 4 = 17–25 %, 5 = 26–35 %, 6 = 36 %–50 %; 7 = 51–65 %, 8 = 66–80 %, and 9 = greater than 80 % of root system galled

^{z}Mean separation within columns by Duncan's multiple range test at $P \leq 0.05$. Means were compared across all temperature and cultivar combinations

Table 9.4 Effect of temperature on root growth and infestation of grapevine rootstocks by *Meloidogyne javanica*

	Jacquez			143 B Mgt		
Treatment	Galling[1]	Egg sacs[2]	Egg[3]	Galling[1]	Egg sacs[2]	Eggs[3]
A. 23 °C/44 days ($572DD_{10}$)	16.2 a	5.2 a	460 a	1.2 a	0.0 a	0 a
B. 23 °C/178 days ($1014DD_{10}$)	62.6 ab	22.2 a	560 a	2.0 a	2.0 a	75 a
C. 33 °C/44 days ($1012DD_{10}$)	41.2 ab	14.6 a	464 a	66.6 ab	16.6 a	396 b
D. 33 °C178 days ($1794DD_{10}$)	613.2 b	613.2 b	855 b	230.6 b	220.6 b	825 b

Treatments which differ significantly ($P \leq 0.05$) are marked vertically with different letters

DD_{10} Physiological time expressed as degree days above a predetermined threshold of 10 °C

[1] Galling is expressed by the number of galls visible per 5 g of new roots under 20× magnification

[2] Egg sacs are expressed by the number visible per 5 g new roots under 20× magnification

[3] Eggs are the average number calculated per egg sac

higher temperature. Chitambar and Raski (1984) also found that the grapevine rootstock cultivars Harmony and Couderc 1613 lost their resistance at 36 °C.

Various stages in the soybean cyst nematode (SCN) disease cycle are affected differentially by temperature and moisture. The highest winter survival of SCN eggs occurs in the colder areas of the continent. Thus, spring inoculum levels may be highest in the northern range of soybean culture. Optimal soil temperatures for egg hatch, root penetration, and juvenile and adult development are 24 °C, 28 °C, and 28–32 °C, respectively; below 15 °C and above 35 °C, little development occurs. Thus, temperature can affect the number of SCN generations per growing season. In theory, with fewer generations, new races will develop less quickly. The more moderate winter temperatures will reduce egg survival, while the higher temperatures in the growing season will increase egg hatch, the rate of nematode development, and, perhaps, the number of generations per season. Soil water is important for SCN movement and development, but water is unlikely to be a limiting factor early in the season. More importantly, the drier growing conditions of summer will increase the yield loss due to SCN because of reduced root surface.

While the exact cause of the recent alfalfa stem nematode outbreak in Yolo County is unclear, an increase in winter temperatures is likely to be an important contributing factor. Stem nematodes do not actively reproduce below 41 °F. In Yolo County, average minimum winter temperatures have increased 3 °F since 1983 and are currently approaching the lower reproductive threshold (Fig. 9.3). Higher temperatures allow the nematode to complete a larger number of breeding cycles during the winter and thus impact the severity of the infestation. If climate change causes winter temperatures to rise further, outbreaks of alfalfa stem nematode may become more frequent in the region. Additionally, the use of organophosphates and carbamate in alfalfa crops has decreased 50 % since 2005. These pesticides are known to suppress stem nematode populations, but are being replaced by pyrethroids, which do not affect the stem nematodes. Consequently, the decreased use of these pesticides may have also played a role in the recent outbreak.

9.5 Expansion of Geographical Distribution

Boag et al. (1991) used data from soil samples collected during the European plant-parasitic nematode survey to assess the possible impacts of climate warming on the geographical range of virus-vector nematodes. Initial analyses of nematode presence–absence data suggested a close association between mean July soil temperature

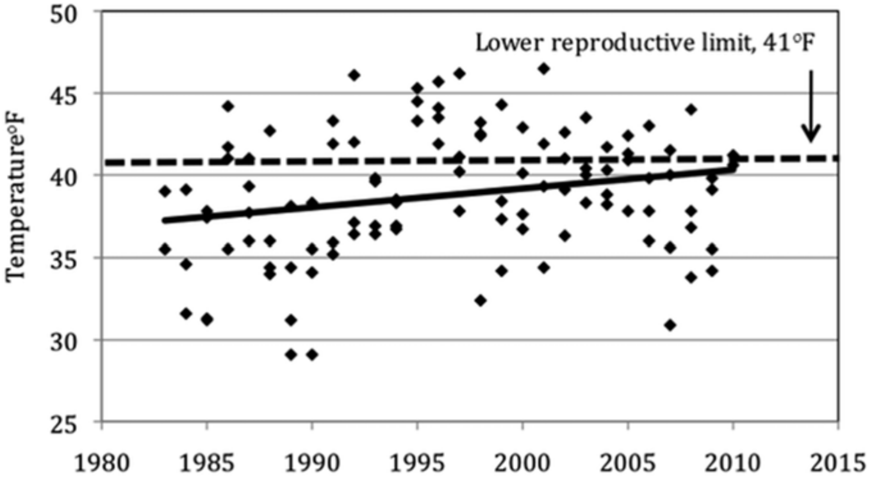

Fig. 9.3 Average minimum monthly ambient temperatures in Davis, California, from November to February 1983–2010. The lower reproductive limit of stem nematode females is 41 °F

and nematode distribution. Based on this result, the authors predicted that climate change could result in increased nematode and virus problems in Northern Europe; they estimated that a 1 °C warming would allow the species in study to migrate northwards by 160–200 km (Neilson and Boag 1996). Although nematodes migrate very slowly, humans are credited with efficiently disseminating them. Hence, nematode spread into new regions could put a wide range of crops at risk; additionally, introduction of new crops into a region could also expose them to infestation by nematode species already present. Changes in precipitation, which were not considered in these analyses, could influence nematode distribution on a large scale, although previous findings had suggested that soil moisture would not affect nematode distribution in most agricultural soils in Northern Europe (Neilson and Boag 1996).

Studies have also demonstrated that the geographical distribution range of plant pathogenic nematodes may expand with global warming spreading nematode problems to newer areas. The soybean cyst nematode (*Heterodera glycines*) is the cause of great economic losses to soybean producers in the USA. The pest has been expanding since the early 1950s, but the increase has been more dramatic since the early 1970s. Before 1970, the soybean cyst nematode was mainly distributed in the Mississippi River Delta area, northern Arkansas, southern Missouri, southern Illinois, and western Kentucky. It is now distributed throughout the main soybean production area and has become the number one soybean pest in the USA (Rosenzweig et al. 2000). In Iowa alone, it caused an estimated yield loss of 201 million bushels (worth about $1.2 billion) during the 1998 growing season (USDA NCR-137 1999). In the northern production region, the nematode has up to three generations per year, depending on planting and weather conditions during the growing season. A longer growing season, associated with a warmer climate, would result in an increased risk of losses similar to the ones reported during the 1998 year. This pest has been monitored and mapped since the 1950s.

Ghini et al. (2008) compared climatological norms from 1961 to 1990 with future scenarios (A2 and B2) of the decades of 2020s, 2050s, and 2080s from five general circulation models (IPCC 2001) to predict the changes in spatial distribution of infestation levels based on number of generations per month in Brazil. They predicted that the nematode infestation will increase in the future due to greater number of generations per month. The number of generations of nematodes will increase in both scenarios, but it will be lower in B2 than A2 scenario.

Using simulated climate change, Carter et al. (1996) predicted that warming will expand distribution of the potato cyst nematode (*Globodera rostochiensis*) and also increase number of generations per year by 2050 in Finland. The predicted effects of climate change on diseases of selected major agricultural and forestry species in Ontario showed that the cyst nematode (*Heterodera glycines*), root lesion nematode (*Pratylenchus* spp.), and pine wood nematode (*Bursaphelenchus xylophilus*) severity increases due to increase in rate of disease development and potential duration of epidemic due to climate change (Boland et al. 2004).

In India, rice root-knot nematode (*Meloidogyne graminicola*), once considered to be a serious pest only in upland rice, has made its importance felt in almost all rice-growing areas and in all types of rice culture including hill ecosystems in recent years (Prasad and Somasekhar 2009; Pankaj et al. 2010).

Neilson and Boag (1996) assessed the possible effect of climate change on the distribution of some common virus-transmitting *Xiphinema* and *Longidorus* species within Great Britain. They observed that theoretically an increase in 1 °C in mean temperature would result in the northward extension of these nematode species by about 160–200 km. Colonization of new areas by virus-vector nematodes has serious implications for agriculture.

9.6 Severe Droughts

Soil nematodes are dependent on the continuity of soil water films for movement. Their activities are largely controlled by soil biological and physical conditions (Yeates and Bongers 1999). Severe droughts resulting in a reduction of soil water will most likely negatively affect soil nematodes.

Increased drought stress reduced pine tree resistance against pine wood nematode (*Bursaphelenchus mucronatus*) and bark beetles. This resulted in rapid tree mortality in pine forests in Switzerland (Robetez and Dobbertin 2004).

Increased water stress due to climate change diminishes plant vigor and alters C:N ratios, lowering plant resistance to nematodes.

9.7 Nematode Management

Climate change will cause alterations in the spatial and temporal distribution of nematodes, and consequently, the control methods will have to be altered to suit these new situations. Assessments of the impact of climate change on nematode infestations and in crops provide a basis for revising management practices to minimize crop losses as climate conditions change (Ghini et al. 2008).

Recent observations suggest that nematode pressure on plants may increase with climate change (Ghini et al. 2008). As a result, there may be substantial rise in the use of nematicides in both temperate and tropical regions to control them. Nonchemical nematode management methods (green manuring, crop rotation, mulching, application of organic manures, etc.) assume greater significance under changing climate scenario.

Climate change-mediated changes in physiology can alter the expression of resistance genes. The most serious threat to genetic resistance to nematodes may be posed by the increased selection pressure resulting from acceleration of nematode developmental rate and increase in number of generations per season due to global warming (Ghini et al. 2008).

Nematode-, bacterial-, and fungal-based biopesticides are highly vulnerable to environmental stress. Increase in temperature and UV radiation and a decrease in relative humidity may reduce the efficacy of these bioagents.

Therefore, there is a need to develop appropriate strategies for nematode management that will be effective under situations of global warming in the future.

9.8 Biotechnological Approaches to Nematode Resistance

Biotechnology offers several benefits for nematode control in an integrated management strategy, such as reducing risks to the environment and to human health, accessibility for food producers in the developing world, and the possibility of achieving durable, broad-spectrum nematode resistance (Thomas and Cottage 2006). A number of genes that mediate nematode resistance have now been or soon will be cloned from a variety of plant species. Nematode resistance genes are present in several crop species and are an important component of many breeding programs including those for tomato, potato, soybeans, and cereals (Trudgill 1991). There are essentially three approaches for engineering resistance: transgenic expression of natural resistance genes in heterologous species, targeting and disruption of the nematode, and feeding site attenuation (Thomas and Cottage 2006).

Using marker-assisted breeding techniques, Monsanto is introducing root-knot nematode resistance into elite genetics to develop cotton varieties that could potentially increase lint yield by an average of 8–10 % under root-knot nematode infestations.

A new, high-throughput screening method is being utilized to accelerate the incorporation of reniform nematode resistance into elite genetics of cotton. The product could potentially increase lint yield by an average of 10–15 % under reniform nematode infestation conditions.

Pineapple plants transformed with the modified rice cystatin gene (proteinase inhibitor) have tested positive for transgene expression, particularly in the root tissue. Cystatin has been shown to deter reniform nematode feeding and reduce populations by interfering with their ability to produce digestive enzymes (Atkinson et al. 1996). The planting of the reniform nematode-resistant pineapple is assumed to replace the current use of fumigants and nematicides in Hawaiian pineapple. This reduction totals to 1.4 million pounds per year in active ingredient with an associated savings of $2.1 million in expenditures.

Potato plants were developed that transgenically expressed a disulfide-constrained peptide (nAChRbp) capable of binding to nematode acetylcholine receptors and inhibiting chemoreception of cyst nematodes. The results validate the root tip-specific promoter of the *Arabidopsis MDK4–20* gene (Lilley et al. 2010) as a means of delivering effective root protection from *Globodera pallida* by the peptide under field conditions.

When susceptible sugar beet genotypes are co-transformed with *Agrobacterium rhizogenes* to introduce the (Hs1.sup.pro-1) resistance gene, the hairy roots formed exhibit resistance to sugar beet cyst nematode (Cai et al. 1997). It was reported that the nematode population decreased by 73 % with experimental resistant varieties whereas that increased by 35 % with a susceptible variety (Werner et al. 1995). A resistant variety called Nematop was developed which showed acceptable performance in nematode-infested soil (Dewar 2005).

For the first time, it has been shown that a Bt Cry6A protein can confer plant resistance to an endoparasitic nematode (*Meloidogyne incognita*) and that Cry 6A proteins have the potential to control plant-parasitic nematodes in transgenic tomato plants (Xiang-Qian et al. 2007).

The *Mi* gene (true *R* gene) from tomato conferred resistance against a root-knot nematode and an aphid in transgenic potato (Rossi et al. 1998).

In the transgenic tobacco plants, AtNPR1 high expression line 19-1 recorded the highest shoot and root weight, which is about fivefold higher, compared to the wild-type plants. The number of root galls and egg masses developed on the infected roots of the transgenic plants was significantly less (up to 50–60 % less) compared to the wild-type plants (Bhanu Priya et al. 2011).

Tobacco plants were engineered to produce dsRNA of two essential genes of the parasitic nematode *M. incognita*. The transgenic tobacco plants very effectively resisted *M. incognita* infection, and their development was severely impaired. These nematodes were specifically deficient in the mRNA of targeted genes, indicating that the dsRNA produced in plants did indeed trigger RNAi response in the nematode (Yadav et al. 2006).

9.9 Conclusions

Research on impact of climate change on soil nematodes has been limited, with most work concentrating on the effects of a single atmospheric constituent under controlled conditions. A few recent experiments have also reported the response of herbivorous nematodes to elevated

CO_2 beyond the trophic group level. Nevertheless, findings of these studies give an insight into the response of nematode trophic groups to climate change and its consequences to agricultural production. Responses of herbivorous nematodes to CO_2 enrichment were observed to be either neutral or positive but not negative. Further, studies predicting changes in geographical distribution of plant-parasitic nematodes using simulation models give a fairly good idea about future scenarios of nematode diseases of plants. More long-term studies in varied ecosystems under different cropping systems of particularly tropical regions are needed to critically assess the impacts of climate change on soil nematodes. This knowledge is vital for developing appropriate adaptation and mitigation strategies to minimize effect of climate change on agriculture.

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10 Impacts on Weeds

Abstract

Weeds compete with crops over nutrients, water, and light and can considerably reduce yields and crop quality. In some cases, weeds can pose human health problems (poisonous plants, allergens) or inhibit harvest. Elevated CO_2, changes in temperature, and precipitation patterns may affect weeds as much as crops. Higher CO_2 will stimulate photosynthesis and growth in C3 weeds and C3 crops and reduce transpiration and increase water-use efficiency in both C3 and C4 weeds and crops. Higher temperatures can possibly offset some of the benefits of elevated CO_2 for both weeds and crops. High temperatures sometimes limit reproductive development, and global warming may decrease reproductive output in such situations despite an increase in CO_2. It is unclear whether this is more likely to occur in C3 than C4 species, but if it were, it could alter weed community compositions and affect crop–weed interactions. This would imply that weed and crops both benefit or lose on the same scale. However, weeds are usually already very competitive due to greater genetic variation and physiological plasticity; otherwise, they would not cause yield losses. Hence, they may gain more advantages from climate change than crops.

In temperate regions, global warming will affect the growth and marginally affect phenology and influence the geographical distribution of weeds. Weed species of tropical and subtropical origins, currently restricted to the southern regions, may expand northward.

Keywords

Weeds • Climate change • Crop losses • Impact • Elevated CO_2 levels • Higher temperatures • Geographical distribution • Increased dispersal • Precipitation effect

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Agricultural weeds can hurt crop yields or increase costs of production by:

- Competing directly for light, nutrients, moisture, and space
- Releasing natural substances that inhibit crop growth (allelopathy)
- Physically hindering crop growth and development, especially climbing vines like morning glories, *Ipomoea* spp., and hedge bindweed, *Calystegia sepium*
- Hosting pests or pathogens that may attack crops
- Promoting disease by restricting air circulation around the crop
- Interfering with or contaminating crop harvest
- Reproducing prolifically, resulting in a greater weed problem in the future
- Parasitizing crops directly (e.g., dodders, *Cuscuta* spp., and witchweed, *Striga asiatica*)

10.1 Crop Losses

The most recent and comprehensive efforts to provide a measure of global crop losses by weeds are those made by Oerke (2006) (Table 10.1). Weeds produced the highest potential loss (34 %). In the USA, annual losses in crop production due to weeds have been valued at approximately US$ 12 billion, amounting to some 10 % of potential production (Patterson and Flint 1990). Large efforts are made to limit these damages through a variety of weed control measures.

Table 10.1 Estimated potential of weeds and actual losses due to weeds in six major crops worldwide, in 2001–2003 (Oerke 2006)

Crop	Attainable production (million tons)	Crop losses (%) due to weeds	
		Potential	Actual
Wheat	785.0	23.0 (18–29)	7.7 (3–13)
Rice	933.1	37.1 (34–47)	10.2 (6–16)
Maize	890.8	40.3 (37–44)	10.5 (5–19)
Potatoes	517.7	30.2 (29–33)	8.3 (4–14)
Soybeans	244.8	37.0 (35–40)	7.5 (5–16)
Cotton	78.5*	35.9 (35–39)	8.6 (3–13)

*Seed cotton

Around the world, more human labor is expended in hand weeding than in any other agricultural task, and most cultivation and tillage practices are designed to aid in weed control. The chemical industry manufactures herbicides, which, next to fertilizers, account for the largest volume of chemicals applied to crops. Among pesticides used for the management of pests, herbicides account for 65 % (IFPRI 1998; USDA 1999).

Most analyses concur that in a changing climate, weeds may become even more active than they are currently, thus posing the threat of greater economic losses to farmers (IPCC 1996; Coakley et al. 1999). While the majority of weeds are invasive species from temperate zones, other weeds in temperate regions originated in tropical or subtropical regions, and in the current climate, their distribution is limited by low temperature. Such geographical constraints will be removed under warm conditions. Warmer temperature regimes have been shown to increase the maximum biomass of the grass weeds significantly. In crop monocultures, undesirable competition is controlled through a variety of means, including crop rotations, mechanical manipulations (hoeing), and chemical treatment (herbicides).

10.2 Climate Change and Weeds

Weeds grown in association with the crops are exposed to increasing concentrations of CO_2 (≥370 ppm) and other active greenhouse gasses (CFCs, CH_4, N_2O, NO_2, etc.) that have led to global warming and the associated greenhouse effect. They are equally and may be differently influenced due to these changes as different species of weeds grow together with a crop. The responses of crop and weeds to increased CO_2 level and temperature are being studied worldwide. The variations in the responses of C4 and C3 plants (both crops and weeds) have been noted under such situations. Composite weeds in the crop fields having variable proportions of C4 and C3 plants are likely to undergo dynamics in weeds insurgence and shift of weeds in favor of certain species in course of time. Increased CO_2

level may stimulate photosynthesis in some weeds, leading to higher growth of rhizomes and other storage organs in perennial weeds, higher seed production in annual weeds, etc., and make their control difficult concurrently or over the seasons/years. Thus, an appropriate technology towards controlling increasingly more difficult perennial weeds will be the important paradigm in future weed research. Climate change is likely to trigger differential growth in crop and weeds and may have more implications on weed control across crops and cropping systems. Some emerging areas of weed research relevant under climate change scenarios are discussed in this chapter.

Climate change may affect invasive plants through:

- Increased disturbance due to fire, floods, and other extreme climatic events
- Potential range shifts (e.g., movement towards cooler latitudes or higher elevations)
- Higher temperatures and reductions in frost events
- Changes in rainfall timing, frequency, and levels (including humidity and evapotranspiration)
- Reduced stream and river flows (exposing well-watered riparian areas)
- Changes in coastal and estuarine habitat due to rising sea levels
- Increased carbon dioxide fertilization (and resultant increases in weed growth)
- Changes in pathogen pressures, including serious impacts on biological control programs
- Changes to flowering and fruiting times
- Changes to species interactions (e.g., between plants and pollinators, weed vectors, etc.)

Climate change is expected to increase the range or "damage niche" (also called "invasion niche") of many weed species. Research suggests that the composition of invasive weed communities will be fundamentally altered by the end of the century under increasing temperature scenarios, with new weed species entering communities as a result of geographic range shifts (McDonald et al. 2009). For example, the range of the yellow star thistle, a California weed, is expected to increase to more northern parts of California and Nevada due to climate change (Bradley et al. 2009).

The effects of climate change on weed–plant interactions are likely to vary by region and crop type. Understanding of the underlying physiological mechanism responses to such factors is needed in order to address these effects. Because the interactions between crops and weeds are "balanced" by various environmental factors, local changes in these factors may tip the scale towards either crop or weed. Furthermore, as the geographic distribution of weed species changes, so will the community composition, posing both challenges and opportunities for invasion control. If the invasion of new weed species can be detected, efforts can be made in advance to prevent and control their establishment.

Changes in temperature and carbon dioxide are likely to have significant direct (CO_2 stimulation of weed growth) and indirect effects (climatic variability) on weed biology. In spite of the importance of weed biology in both the environment and in farms, very little is known regarding the impact of these environmental changes on either the reproductive success of agronomic or invasive weeds or the potential consequences for their management. Yet, given what is known, it is clear that the agricultural, environmental, and health costs of not understanding the impact of CO_2 on weed biology may be substantial. It is hoped therefore that the current chapter may serve to both emphasize the critical nature of this topic and to serve as an initial guide to those who wish to recognize the ramifications of rising CO_2 beyond the polemic of global warming.

10.3 CO_2 Enrichment

Higher CO_2 will stimulate photosynthesis and growth in C3 weeds and C3 crops and reduce transpiration and increase water-use efficiency in both C3 and C4 weeds and crops (Fig. 10.1). Due to their different types of photosynthesis, C4 and C3 plants react very differently to elevated atmospheric CO_2. Basically elevated CO_2 does not directly stimulate C4 photosynthesis and growth. Nonetheless, drought stress can be

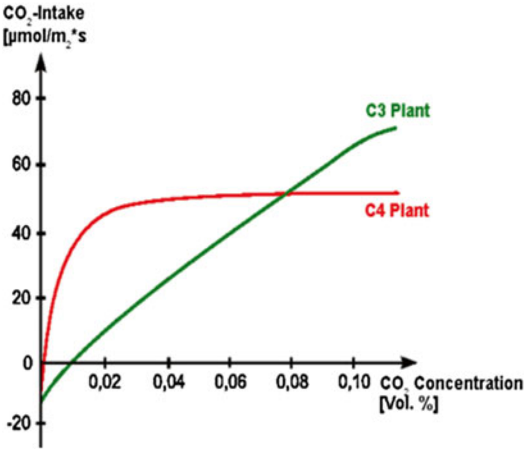

Fig. 10.1 Comparison of CO_2 intake of C3 and C4 plants in relation to atmospheric CO_2 concentrations. At current CO_2 levels (380 ppm), CO_2 saturation in C4 plants is achieved

ameliorated at elevated CO_2 as a result of even lower stomatal conductance. Therefore, unlike C3 crops for which there is a direct enhancement of photosynthesis by elevated CO_2, C4 crops will only benefit from elevated CO_2 in times and places of drought stress. Figure 10.1 shows the different responses of C3 in comparison to C4 plants to CO_2 increase. CAM plants react to elevated CO_2 similar to C3 plants with enhanced growth, if water supply is sufficient. If not, they will respond like C4 plants.

C3 weeds (using one of two types of photosynthetic pathway, which responds to higher levels of CO_2) such as parthenium (*Parthenium hysterophorus*) may grow more rapidly under higher carbon dioxide levels and become more competitive (McFadyen 2008; Poorter and Navas 2003).

CO_2 can affect plant and leaf size, seed size and production, the nutritiousness of leaves to herbivores, plant toxicity, and pollen production.

Nitrogen-fixing weeds, such as brooms, gorse, and acacias, may especially benefit because growth stimulated by CO_2 will not be constrained by low nitrogen levels (Poorter and Navas 2003).

Under high CO_2, C3 plants are likely to become more water efficient (Ghannoum et al. 2007), potentially allowing weeds such as prickly acacia and rubber vine (*Cryptostegia grandiflora*) to move into drier habitats (Kriticos et al. 2003).

Vines respond strongly to higher CO_2 levels (Gallagher et al. 2006), and there are many highly damaging invasive vines (cat's claw *Macfadyena unguis-cati* and rubber vine) that could benefit.

Higher CO_2 levels are likely to reduce the effectiveness of glyphosate, the main chemical used to control environmental weeds in Australia (Ziska and Goins 2006; Ziska and Runion 2007).

However, since climatic change, especially increased CO_2 affects C3 and C4 plants differently, and different combinations must be investigated separately:

- C4 weeds in C3 crops
- C3 weeds in C3 crops
- C3 weeds in C4 crops
- C4 weeds in C4 crops

When solely looking at the benefit of elevated CO_2, it would be possible to argue that C4 weeds such as barnyard grass (*Echinochloa crus-galli*) and redroot pigweed (*Amaranthus retroflexus*), which do not react to elevated CO_2 with more biomass production, would be less competitive than C3 crops which grow better under increased CO_2 and vice versa; in C4 crops like millets, sorghum, maize, and sugarcane, C4 weeds may become less competitive than C3 weeds.

10.3.1 C4 Weeds in C3 Crops

Among 14 of the world's worst weeds are C4 plants, while around 76 % of the harvested crop area in 2000 was grown with C3 crops (Monfreda et al. 2008). If the hypothesis is right that C3 crops would benefit more from elevated CO_2 than C4 weeds, losses due to C4 weeds might decrease. In the early 1980s, experiments were conducted to prove this kind of hypothesis (Patterson and Flint 1990), and basically, the hypothesis was supported (Coleman and Bazzaz 1992; Ziska 2003). However, more research has been done manipulating CO_2 concentrations alone. Temperature increase or drought in combination with elevated CO_2 was less investigated (Bunce and Ziska 2000). When including temperature increase, trends are not clear and will depend on the local conditions. Optimal temperatures for growth in C4 plants are generally higher than optimal temperatures for C3 plants, but with higher CO_2, the optimum temperature of many C3 plants also increases (Bunce and Ziska 2000).

However, looking at photosynthesis and temperature alone might be insufficient. The barnyard grass (*Echinochloa crus-galli*) in combination with a mycorrhiza also benefits from elevated CO_2 levels. In drought situations, C4 weeds might also have advantages over C3 crops under elevated CO_2.

10.3.2 C3 Weeds in C4 Crops

The benefit of elevated CO_2 under sufficient water condition will lead to higher C3 weed competitiveness in C4 crops. An experiment with sorghum and a C3 and C4 weed showed what the potential implications increased CO_2 level may have on the crops. Under ambient CO_2, the presence of the C3 weed velvetleaf (*Abutilon theophrasti*) had no significant effect on either sorghum seed yield or total aboveground biomass; however, at elevated CO_2, yield and biomass losses were significant. The additional loss in sorghum yield and biomass was associated with a threefold increase in velvetleaf biomass in response to increasing CO_2 (Ziska 2003).

Elevated CO_2 alone might not only lead to an increase of pure biomass of C3 weeds. The dandelion (*Taraxacum officinale*) produced more fertile seeds and eventually larger seedlings.

However, C4 crops might outcompete better growing C3 weed in drought situations and at higher temperatures utilizing mycorrhiza.

10.3.3 C3 Weeds in C3 Crops

Logic would imply that the same type of plants (with regards to photosynthesis) in the same ecosystem would react to changes in a similar way. This is only partly true, while C3 crops and C3 weeds both benefit from elevated CO_2, it seems that the magnitude varies. Stimulation of biomass accumulation from CO_2 doubling was estimated by one research team to be +31 % in wheat, +30 % in barley, +27 % in rice, +39 % in soybean, +57 % in alfalfa, and +84 % in cotton. In contrast, a survey of experimental results on 27 non-crop C3 species revealed that biomass accumulation increased from 79 to 272 % compared to ambient CO_2 (Patterson 1995). An experiment, which investigated seven C3 crop and three C3 weeds at 350 and 700 ppm CO_2, showed similar growth rates and mass of C3 crops and C3 weeds (Bunce 1997).

10.3.4 C4 Weeds in C4 Crops

Since all C4 plants (weeds and crops) have the same photosynthesis path, they may react to changes in the same ecosystem in a similar way. However, research on impact of climate change in this combination has not been done.

10.4 Elevated Temperatures

Higher temperatures can possibly offset some of the benefits of elevated CO_2 for both weeds and crops. High temperatures sometimes limit reproductive development and global warming may decrease reproductive output in such situations despite an increase in CO_2. It is unclear whether this is more likely to occur in C3 than C4 species, but if it were, it could alter weed community compositions and affect crop–weed interactions (Bunce and Ziska 2000).

In temperate regions, global warming will affect the growth and marginally affect phenology and influence the geographical distribution of weeds. Weed species of tropical and subtropical origins, currently restricted to the southern regions, may expand northward (Patterson 1995). Warmer seasonal temperatures and milder winters will extend the distribution of invasive weeds (Kudzu and Ragweed).

Increasing temperatures may mean an expansion of weeds into higher latitudes or higher altitudes. Very aggressive weeds that are currently found in the south are limited in the northern states by low temperatures. Many C4 grass weeds are serious problems in the southern USA but do not occur at problem levels in the US Corn Belt. Studies have shown that itch grass, a profusely tillering, robust grass weed, could invade the central Midwest and California with only a 3 °C warming trend (Patterson 1995). Witch weed, a root parasite of corn, is limited at this time to the coastal plain of North and South Carolina. With an increase of temperature of 3 °C, it is speculated that this parasite could become established in the Corn Belt with disastrous consequences. The current distribution of both Japanese honeysuckle and kudzu is limited by low winter temperatures. Global warming could extend their northern limits by several hundred miles.

As mean temperatures increase, some weeds will be able to expand their range into new areas. The tropical weed prickly acacia (*Acacia nilotica* ssp. *indica*) is likely to spread south (Kriticos et al. 2003) and athel pine could spread throughout inland rivers as far south as the Murray River in Victoria.

10.5 Expansion of Geographical Distribution

Lowland species such as lantana (*Lantana camara*) may be able to shift into the uplands (McFadyen 2008). Weeds moving into alpine areas could have a particularly severe impact because many alpine plant communities are localized with rare endemic species, and there are numerous weed species at lower altitudes (McDougall et al. 2005). On subantarctic Heard Island, the weed winter grass (*Poa annua*) has been spreading rapidly on deglaciated sites (Scott and Kirkpatrick 2005).

The number of documented examples to promote potential range expansion in invasive plants is increasing, and many of these are related to key aspects of climate change, such as northward range expansion in the northern hemisphere (Table 10.2).

Table 10.2 Actual recorded range expansions of weeds or weed genotypes in the USA and Canada and associated adaptive traits

Weed species	Description of range expansion	Adaptive traits	References
Datura stramonium (Jimsonweed)	Northward invasion of Canadian and northeastern US cropland since the 1950s	Heavier seeds, earlier growth	Weaver et al. (1985) and Warwick (1990)
Hypericum perforatum (St John's wort)	Clinal variation across the north–south axis of North American distribution	Leaf size larger in northern populations	Maron et al. (2004)
Echinochloa crus-galli (barnyard grass)	Northward invasion of Quebec from the USA in the nineteenth century	More rapid maturation at each life cycle stage	Potvin (1986)
Panicum miliaceum (proso millet)	Northward invasion into Canadian cropland by the early 1970s	Seed germination and dispersal characteristics	Bough et al. (1986), McCanny et al. (1988), and McCanny and Cavers (1988)
Polygonum cuspidatum (Japanese knotweed)	Range expansion in both Ontario and British Columbia, Canada	Genotypes with different temperature thresholds and potential hybridization	Bourchier and Van Hezewijk (2010)
Setaria faberi (giant foxtail)	Northward expansion into Canadian cropland by the 1970s	Varied life history traits	Warwick et al. (1987)
Setaria viridis (green foxtail)	Survival at Churchill, Manitoba at nearly 60N latitude (normal range 45–55N)	Leaf production at low temperatures	Douglas et al. (1985) and Swanton et al. (1999)
Sorghum halepense (Johnson grass)	Northward expansion by 5 latitude between 1926 and 1979	Northern populations annual (versus perennial southern population)	Warwick et al. (1986)

10.6 Varying Precipitation Patterns

Response to drought in agronomic conditions is dependent on species and cultural conditions. Any factor which increases environmental stress on crops may make them less competitive with weeds (Patterson 1995).

Weeds constrained by rainfall may also find new habitats under new climate conditions. Lantana and mist flower (*Eupatorium riparium*), for example, could expand if rainfall increased in some areas (McFadyen 2008).

10.7 Increased Dispersal

If fruit-eating birds arrive earlier and leave later for migration, as has been occurring, fruit-bearing weeds may benefit from greater dispersal.

Higher temperatures and other factors are likely to increase insects' breeding cycles and provide more weed pollination (Gallagher et al. 2006).

As animals, including invasive species, move into new areas in response to climate change, they are likely to spread weeds or create disturbance advantageous for weeds.

10.8 Extreme Weather Events

Extreme events including droughts, floods, and cyclones can sometimes create ideal conditions for weeds to extend their range and invade new areas or outcompete native species in their existing range.

Dry soil conditions caused by drought prolong the longevity of weed seed banks; and importing fodder and grain into drought areas can bring new weed problems to the region. Drought can reduce the competitiveness of native vegetation, providing new opportunities for weed invasion.

Floods can spread weeds along water courses into areas that were previously free of weeds. By washing away vegetation and exposing areas of disturbed soil, floods can also provide opportunities for new weed invasions by reducing competition from existing plants.

Cyclones can create new opportunities for weed invasion through associated flooding, soil movement, and damage to native vegetation communities. During cleanup activities, it is important to limit further spread by minimizing the movement of soil or plant material from one area to another.

When native vegetation is stressed or destroyed by droughts, fires, floods, or severe storms, weeds gain new opportunities to replace native species.

There is a huge pool of invasive plants available to colonize bare spaces left by drought, fire, and storm damage, and wind and flooding waters help spread weeds.

Many of Australia's worst weeds benefit from extreme events, including at least 13 of the country's 20 weeds of national significance. Athel pine (*Tamarix aphylla*), for example, spread along 600 km of the Finke River in central Australia after severe flooding in the 1970s and 1980s, replacing river red gums. It could spread much further under climate change.

Serrated tussock (*Nassella trichotoma*) benefits from bare patches created by droughts, marram grass (*Ammophila arenaria*) and bitou bush (*Chrysanthemoides monillfera rotundata*) from storms, and willows (*Salix* spp.) from floods. Climate change-altered fire regimes will also favor some weeds, particularly fire-promoting exotic pasture grasses.

10.9 Human Health

Weeds are recognized by the general public as significantly affecting human health either through allergenic reactions, skin irritations, mechanical injury, or internal poisoning (Ziska 2001). For the most part, we are only in the initial stages of quantifying how changes in climate and/or CO_2 may affect those specific weeds associated with public health. One exception has been changes in pollen production and allergenicity in common ragweed (a recognized cause of allergic rhinitis) with changing CO_2 and temperature in both indoor (Ziska and Caulfield 2000; Wayne et al. 2002) and in situ experiments (Ziska et al.

2003). Additional research on how rising CO_2 can affect both poison ivy growth and toxicity is currently ongoing. No information is available on how CO_2 could alter the toxicity of secondary compounds associated with mortality in weedy species.

10.10 Weed Management

Clearly, any direct or indirect impacts from a changing climate will have a significant effect on chemical weed management. Changes in temperature, wind speed, soil moisture, and atmospheric humidity can influence the effectiveness of applications. For example, drought can result in thicker cuticle development or increased leaf pubescence, with subsequent reductions in herbicide entry into the leaf. These same variables can also interfere with crop growth and recovery following herbicide application. Overall, herbicides are most effective when applied to plants that are rapidly growing and metabolizing, i.e., those free from environmental stress. But does rising CO_2 per se alter chemical management? There are an increasing number of studies (Ziska et al. 1999, 2004; Ziska and Teasdale 2000) that demonstrate a decline in chemical efficacy with rising CO_2. The basis for this reduction is unclear. Recent work with Canada thistle grown in monoculture under field conditions suggested a greater root-to-shoot ratio and subsequent dilution effect of glyphosate when grown at elevated CO_2 (Ziska et al. 2004). However, it is not clear if this is a ubiquitous response. In any case, if CO_2 does reduce efficacy, then additional work is needed to determine herbicide specificity, concentration, and application rates as possible means of adaptation.

Biological control of pests by natural or manipulated means is likely to be affected by increasing atmospheric CO_2 and climatic change. Climate as well as CO_2 could alter the efficacy of weed biocontrol agents by potentially altering the development, morphology, and reproduction of the target pest. Direct effects of CO_2 would also be related to changes in the ratio of C/N and alterations in the feeding habits and growth rate of herbivores. As pointed out by Patterson (1995), warming could also result in increased overwintering of insect populations and changes in their potential range. Although this could increase both the biological control of some weeds, it could also increase the incidence of specific crop pests, with subsequent indirect effects on crop–weed competition. Overall, synchrony between development and reproduction of biocontrol agents and their selected targets is unlikely to be maintained in periods of rapid climatic change or climatic extremes. Whether this will result in a positive or negative benefit remains unclear.

A standard means of controlling weed populations and the one most widely used in developing countries is mechanical removal. Tillage (by animal or mechanical means) is regarded as a global method of weed control in agronomic systems. Elevated CO_2 could lead to further belowground carbon storage with subsequent increases in the growth of roots or rhizomes, particularly in perennial weeds. Consequently, mechanical tillage may lead to additional plant propagation in a higher CO_2 environment, with increased asexual reproduction from belowground structures and negative effects on weed control (e.g., Canada thistle) (Ziska et al. 2004).

Overall, there are strong empirical reasons for expecting climate and/or rising CO_2 to alter weed management. Adaptation strategies are available, but the cost of implementing such strategies (e.g., new herbicides, higher chemical concentrations, new biocontrol agents) is unclear. Herbicide use is controlled by individual state regulations. If an increase in CO_2 and temperatures allow invasive weed species to expand their geographical locations, new herbicides may be needed to combat them. Often it takes a period of time to receive state approval of a new chemical or a chemical that has not been previously used.

10.11 Mitigation

10.11.1 Selective Allelopathy and Self-Supporting Weed Management

Studies involving allelopathic crop residue mulches (maize, sorghum, wheat, barley, or rye) may help to mitigate adverse climatic effects.

Effective utilization of such crop residue mulches can act as self-supporting weed management (rice) for the concurrent as well as rotational crops.

10.11.2 Soil Solarization Studies

Soil solarization plays a big role in the management of weeds, nematodes, and pathogens under the conditions of increased temperature. It can be incorporated in the schedule of integrated weed management (IWM) and integrated pest management (IPM). However, the thickness and color of polyethylene, time and duration of solarization, effect on beneficial microorganisms and nutrient mineralization, and supplementary treatments to be superimposed or followed after solarization across situations need to be more characterized/refined under the changing climate.

10.11.3 Chemical Weed Control Studies Using Old and New Molecules of Herbicides

Climate change, particularly increased temperature, may have profound impact on the control of composite, parasitic, aquatic, and invasive weeds using herbicides in crops and non-cropped situations. Studies on the ED_{50} or GR_{50} value and efficiency of herbicides are of paramount importance under this situation. Monitoring of residues in soil, water, and plants may add another dimension of research. The following studies may have priority:

- Herbicide bio-efficacy, biochemical selectivity, and nontarget toxicity of the old and new herbicides and their formulations
- Herbicide resistance management
- Herbicide-resistant crops (transgenics) and their performance evaluation

10.11.4 Integrated Weed Management

Integrated weed management (IWM) is the recent and more acclaimed aspects of long-lasting weed management program in crops and non-cropped situations. Integrated weed management lies at the center of weed control. The combination of farming strategies, biological control agents, and necessary herbicide use has helped California farmers address weed problems using a variety of methods.

10.11.5 Conservation Agriculture and Weed Management

Weed management under minimal and zero tillage poses a big challenge to crop production and appears to be another important aspect of research across crops and situations. Resource conserving techniques need to be blended with other options towards better weed control under conservation agriculture.

10.11.6 Remote Sensing and Site-Specific Weed Management

Combined use of remote sensing, Geographic Information System (GIS), and Global Positioning System (GPS) is a powerful tool in detecting, mapping, and monitoring the spread of weeds over inaccessible areas. Identification of weed species using remote sensing in range or wild range lands can be achieved. Site-specific weed management (SSWM) may be undertaken using these tools. Computer-analyzed video images of the digital data can provide the area estimates of weeds.

10.11.7 Other Methods

Crop rotations should be followed to increase biodiversity. Noxious weeds establish slower (grassy weeds in cereals), because specific relationships between weeds and host plants are interrupted (Dhawan and Peshin 2009).

Biological control agents can be effective against weed populations that are resistant to herbicides. Planting strategies such as changing planting times can counter weed growth.

In addition to the prudent application of herbicides, increased use of nonchemical weed controls would help minimize crop losses (Pimentel et al. 1993). Nonchemical controls include crop rotations, biological controls, altering planting dates and fertilizer and irrigation applications, and soil management and tillage. These technologies could help minimize projected weed losses and thereby help maintain crop yields.

10.11.8 Transgenic Herbicide-Tolerant Crops

Another important issue regarding pest management in the future centers on the role of biotechnology in crop protection. The next 20 years will likely see a substantial increase in the use of genetically engineered plants. Some of these plants have been engineered so that the application of herbicides destroys weeds but not the economic crop. Other genetically engineered plants have been designed to resist pests such as stem borers and nematodes without the need for pesticides. Others are expected to combine both herbicide resistance and insect resistance in one seed.

The Roundup Ready (RR) technology incorporates genetic resistance to glyphosate into crop plants by inserting a single bacterial gene that modifies 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase, an enzyme essential for plant growth.

GTS 40-3-2 (also known as Roundup Ready Soybean) is a genetically engineered variety of glyphosate-resistant soybeans produced by Monsanto. The major problem in soy farming is weeds; thus, GTS 40-3-2 is revolutionary. The most widely utilized herbicide-tolerant crop in production today is the Roundup Ready soybean resistant to the broad spectrum herbicide Roundup that contains the active ingredient glyphosate.

LibertyLink soybeans were introduced in 2009. These soybeans allow the use of Ignite herbicide as a postemergence treatment. Ignite is a newer, more concentrated formulation of Liberty herbicide. This gives soybean producers an option to Roundy Ready soybeans.

Roundup Ready Corn (RR Corn) is a genetically engineered corn that has had its DNA modified to withstand the herbicide glyphosate (the active ingredient in Monsanto's herbicide Roundup). It is also known as "glyphosate-tolerant corn."

LibertyLink corn is genetically engineered for tolerance to over-the-top applications of the nonselective herbicide Liberty (glufosinate ammonium).

Dicamba-**,** glufosinate-, and glyphosate-tolerant corn is designed to build on the Roundup Ready Xtend Crop System and provide farmers with additional herbicide-tolerance options. This product would contain multiple herbicide-tolerance traits enabling use of herbicides with different modes of action, expanding growers' options to protect their crop from weed infestations.

Using modern biotechnology, Monsanto Company has developed Roundup Ready cotton plants that confer tolerance to glyphosate, the active ingredient in Roundup agricultural herbicides.

LibertyLink cotton has been genetically modified to be tolerant to Liberty herbicide, allowing for effective postemergence herbicide management system in cotton.

Roundup Ready canola has been modified using gene technology to tolerate glyphosate, the active ingredient in Roundup agricultural herbicides.

The LibertyLink trait (glufosinate resistance) is available in top-performing InVigor canola hybrids.

Roundup Ready sugar beets have been enhanced through biotechnology and contain the Roundup Ready gene to tolerate applications of labeled Roundup agricultural herbicides, which contain the active ingredient glyphosate.

Ribas et al. (2006) introduced the *bar* gene in *Coffea canephora* and *C. arabica*. The *bar* gene inactivates the herbicide ammonium glufosinate, which is normally used as a nonselective pre-emergence herbicide and also for preharvest desiccation.

Commercially available genetically modified herbicide-tolerant crops are presented in Table 10.3 (Castle et al. 2006).

Table 10.3 Commercially available genetically modified herbicide-tolerant crops (Castle et al. 2006)

Crop	Trait phenotype	Target trait gene(s)	Trait designation	Originating company	Year of first commercial sale	Trade name
Cotton	Resistance to glyphosate herbicides	CP4 epsps	MoB1445/1698	Monsanto	1996	Roundup Ready
	Resistance to phosphinothricin herbicides	bar	LLCotton25	Bayer Crop Science	2005	LibertyLink
Corn	Resistance to glyphosate	Maize epsps	GA21	DeKalb (now Monsanto)	1998	Roundup Ready
		Two CP4 epsps expression cassettes	NK603	Monsanto	2001	Roundup Ready Corn 2
	Resistance to phosphinothricin herbicides	pat	T14, T25	Aventis (now Bayer Crop Science)	1996	LibertyLink
Soybean	Resistance to glyphosate herbicides	CP4 epsps	GTS-40-3-2	Monsanto	1996	Roundup Ready
Canola	Resistance to glyphosate herbicides	CP4 epsps, gox v247	GT73	Monsanto	1996	Roundup Ready
	Resistance to phosphinothricin herbicides	pat	Topas 19/2	Agrevo (now Bayer Crop Science)	1995	LibertyLink
Alfalfa	Resistance to glyphosate herbicides	CP4 epsps	J101, J163	Monsanto	2005	Roundup Ready

10.12 Research Needs

Climate change is listed as a key threatening process under the Environment Protection and Biodiversity Conservation Act 1999. Governments should undertake adaptation research and develop action plans to reduce the impact of climate change:

- Identifying priority areas for research and monitoring of the response of invasive plants to climate change.
- Monitoring, recording, and analyzing changes in distribution, abundance, and impact of invasive plants to ensure management practices are adapted to minimize future impacts on biodiversity and primary production.
- Developing adaptation methodology and initiatives that reduce the impacts of invasive plants on biodiversity in future climates and incorporating these into management actions in conjunction with NRM regional bodies and other stakeholders.
- Research and understanding the interactions between climate change, weeds, biodiversity, and primary production, including negative and positive impacts: improving knowledge of those impacts to develop specific impact reduction actions. This includes planning for situations where invasive plants may provide ecosystem functions (connectivity, harbor) that may no longer be provided by native species under altered climates.
- Raising community awareness and sharing knowledge of the increased impacts of invasive plants on biodiversity and primary production under climate change: providing opportunities for public participation in impact reduction actions.

10.13 Conclusions

The effects of climate change on weed–plant interactions are likely to vary by region and crop type. Understanding of the underlying physiological mechanism responses to such factors is needed in order to address these effects. Because the interactions between crops and weeds are "balanced" by various environmental factors, local changes in these factors may tip the scale towards either crop or weed. Furthermore, as the geographic distribution of weed species changes, so will the community composition, posing both challenges and opportunities for invasion control. If the invasion of new weed species can be detected, efforts can be made in advance to prevent and control their establishment.

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Impacts on Integrated Pest Management

11

Abstract

During the past decade, higher education institutes, research managers, and investors have shifted focus away from traditional crop protection towards crop resistance with a subsequent decline in resources for broader plant health and integrated pest management (IPM). This has reduced the ability of crop protectionists to take full advantage of the many new technologies available today for managing crop health. The momentum and impact that IPM has had in the past on pests, especially insects, diseases, and weeds as they affect crop health and food security, need to be expanded and taken to a new level. A potential exists for yields to increase well beyond those attained by the green revolution while reducing human and environmental costs.

Improvements in IPM can lead to sound crop health management (CHM) programs that contribute towards resolving the unprecedented challenge to food security facing the international community. This, however, requires looking at CHM in the wider context of climate change, trade globalization, environmental protection, and the role of agriculture for economic growth to alleviate poverty.

Keywords

Integrated pest management • Crop health management • Insects • Diseases • Weeds

11.1 Introduction

The harmful pests (insects, pathogens, nematodes, weeds, rodents, and other animals) are responsible for significant losses that are estimated to vary from 26 to 40 % of the attainable (uninjured) yield in major food and cash crops (Oerke 2006).

Integrated pest management is an important principle on which sustainable crop protection can be based. IPM allows farmers to manage pests in a cost-effective, environmentally sound,

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and socially acceptable way. According to FAO, IPM is defined as "A pest management system that in the context of the associated environment and the population dynamics of the pest species utilizes all suitable techniques and methods, in a compatible manner as possible and maintains the pest populations at levels below those causing economic injury."

11.1.1 Advantages of Integrated Pest Management (IPM)

By bringing technology to farmers, IPM has been instrumental in increasing agricultural productivity and sustainability and reducing pesticide misuse in the developing world. IPM in potato and sweet potato in Latin America has shown an internal rate of return on investment of 27–49 %, a very high level when compared with other types of investment in agricultural research; moreover, the adoption of IPM brought additional net benefits to farmers ranging from US$100 to 536/ha (Ortiz et al. 2009). Pretty et al. (2006) have also shown that IPM technologies have effected a decline of 71 % in pesticide use, while yields increased by 42 %. Different approaches based on IPM have been developed in the French West Indies in banana cultivation and have led to a 65 % decrease in pesticide use over the last 10 years (Côte et al. 2009).

IPM is needed to protect the sources of resistance presently available and to supplement situations where only lower levels of resistance or tolerance are available. Considering the approaching food insecurity, there is an urgent need to modernize IPM programs and to continually integrate established and new technologies for the improvement of crop, environmental, and human health.

11.1.2 New Approach

A major element in maintaining crop health is the naturally occurring ecosystem services, such as predators, parasites, and antagonists for all pests, especially insects. Other control interventions are standard practices in crop protection such as rotation, planting form, trap cropping, mulching, biorationals, pheromones, allomones, and the judicious use of safe pesticides.

During the past decade, higher education institutes, research managers, and investors have shifted focus away from traditional crop protection towards crop resistance with a subsequent decline in resources for broader plant health and IPM. This has reduced the ability of crop protectionists to take full advantage of the many new technologies available today for managing crop health. The momentum and impact that IPM has had in the past on pests, especially insects, diseases, and weeds as they affect crop health and food security, need to be expanded and taken to a new level. A potential exists for yields to increase well beyond those attained by the green revolution while reducing human and environmental costs.

Crop health is a major element in the highly productive systems of modern agriculture. Developing countries, where modernization has not yet taken complete hold, will continue to be deprived of adequate food and access to global markets if they do not deploy the wide range of IPM technologies available for crop health stability.

If the least developed countries are to be part of the global community, this situation needs major correction, and improved IPM systems are the key to achieving it. Farmers in developing countries can be part of the big picture and benefit from a wide range of IPM technologies that promote crop health and domestic food security (Table 11.1).

Improvements in IPM can lead to sound CHM programs that contribute towards resolving the unprecedented challenge to food security facing the international community. This, however, requires looking at CHM in the wider context of climate change, trade globalization, environmental protection, and the role of agriculture for economic growth to alleviate poverty.

11.2 Crop Health and Integrated Pest Management

One area where increased investment in science would significantly enhance efforts to more effectively manage current and future risks from pests is

Table 11.1 Relative returns from selected crop health management options to land owners and farm laborers

	Crop health management options					
Factor owners	Cultural practices	Physical control	Biological control	Biopesticides	Host plant resistance	Chemical pesticides
Small land owners	3	2	2	2	3	1
Medium land owners	2	2	3	3	3	2
Large land owners	1	3	3	3	3	2
Laborers	3	2	1	2	1	1

Norton (2010), modified
3 high, 2 medium, 1 low
1. Mulching, pruning, early harvesting and planting, grafting, rouging, host-free period, hand weeding
2. Soil solarization, hot water treatment, pheromone traps, sticky traps, bagging fruits, hand picking insects, irradiation
3. Classical biocontrol, augmentative release, exchange or redistribution of natural enemies between regions
4. *Trichoderma, Pseudomonas, Bacillus subtilis*, nuclear polyhedrous virus, Bt, neem, entomopathogenic fungi and nematodes
5. Conventional and marker-assisted breeding, genetically modified crops
6. Synthetic insecticides, nematicides, fungicides, herbicides. Relative returns in the short and long run may differ, and these ratings are short run. They also differ by pesticide class

CHM. For example, climate change could impair the reliability of current CHM strategies, requiring additional resources to develop new knowledge systems and appropriate IPM measures to counter new pests or the intensification of existing ones. A two-pronged strategy therefore needs to be developed that would aim at managing current pest threats more effectively while at the same time laying a foundation for addressing future threats. Such a strategy will produce a strong adaptation–development synergy (Table 11.2), particularly in the developing world where adequate resources to manage pests are lacking.

In developing long-term investment strategies for adapting CHM systems to meet future challenges, the priority should be to undertake comprehensive research and assessment of how pest threats could evolve under climate change and whether current and emerging IPM technologies will be adequate to offset these threats to crop health. This information is notably absent in the most recent assessment by the IPCC, despite the threat that biotic stresses pose to future food production and food security. In addition, investments in infrastructure, training, and education are needed in order to manage existing pest problems better, as well as to develop sufficient knowledge and capacity to aid the crop protection specialist – and finally the farmer – in responding to new threats.

11.3 Enhancing the Impact of IPM on Crop Health Management

11.3.1 Scientific Solutions

Despite the obvious gains from IPM, the adoption rates of many new and effective technologies are still low. Research institutions have decades of experience in IPM, soil fertility research, plant breeding, agronomy, and socioeconomic research and are very well positioned to provide science-based solutions for CHM in developing countries. To build and expand on past successes, collaboration among centers, in partnerships with advanced research institutions and private industry, has to be fostered and harnessed with Systemwide Program on Integrated Pest Management (SP-IPM).

Together, these partners should focus on three major cross-cutting research areas: climate change; food, feed, and environmental safety; and agroecosystem resilience. Within these areas, the newest research methodologies are being employed to obtain a better understanding of the nature and extent of biotic stresses to crops in a range of agroecological zones and production systems. This will ultimately support the development of advanced technologies for a sustainable increase in crop yields at the farm level in developing countries. This team of IPM scientists

Table 11.2 Major contributions of crop health management

Major contributions	Management of current and future pest threats
Economic sustainability	Reduces sanitary and phytosanitary risks
	Provides a framework for the payment of ecosystem services
	Improves profitability
	Reduces externalities
Environmental sustainability	Conserves natural resources including fossil fuels, soils, water, and biodiversity
	Provides ecosystem services: pollination, clean waterways, watershed protection, diverse landscapes, biodiversity-rich ecosystems
	Reduces the recurrence of pests and resurgence of secondary pests
Social/cultural sustainability	Changes the attitudes of farmers towards stewardship
	Increases farmers' knowledge of ecosystem function
	Is locally adaptable and compatible with social and cultural values
	Allows different weighting of desired outcomes based on social norms
Poverty alleviation	Generates local input markets
	Generates economic growth through increased production
Climate change/land use	Mitigates climate change through reduced carbon emissions and increased sequestration
	Reduces the need to convert forest land into agricultural land
	Provides a framework for adaption to pest outbreaks and changes for risk distribution
Food safety and health	Reduces the risk of mycotoxin exposure
	Protects the efficacy of pesticides in the control of vectors of human diseases
	Reduces the risks of pesticide residues in food, feed, and fiber
	Improves water quality through reduced pesticide runoff
	Minimizes the risk of contamination by human pathogens
Food security	Reduces the risks of pre- and postharvest losses
	Increases productivity
	Reduces food prices to benefit consumers
	Improves the availability of food at all levels of consumption

should also engage in capacity development at the policy maker, research manager, scientist, and extension agent levels to improve the capacity for innovation, adaptation, and adoption in partner countries. This collaborative research within SP-IPM fits squarely into the emerging concept of Consortium Research Programs developed as a new mode of delivery for cutting-edge research.

11.3.1.1 Climate Change

The multiple impacts of climate change could significantly reduce the effectiveness of current IPM strategies, leading to higher crop losses. Better knowledge and understanding of pest behavior under different projected climatic scenarios are required to adopt and develop new IPM technologies to respond to threats resulting from climate change. It is predicted that changing climates will cause pests to spread further, covering more areas that increasingly become suitable for them, and to multiply faster in current areas. The potential effect of climate change on pests, and the responses of individual species, could lead to major shifts in biodiversity and species composition. In this respect, divergences in the thermal preferences of pests and their natural enemies might lead to a disruption of temporal or geographic synchronization, increasing the risk of pest outbreaks. Additionally, increased concentrations of CO_2 and tropospheric ozone in the atmosphere may alter the secondary chemistry of crops and their susceptibility to insects and diseases. Increased tropospheric ozone is a particular problem in many areas of the developing world, and crops such as rice, wheat, soybean, mung bean, groundnut, and chickpea are already suffering the effects of high regional ozone levels.

The research institutes should respond to threats resulting from climate change by carrying out collaborative research and surveillance to evaluate the changes in cropping systems and production practices affected by it and to find out which cropping systems are the most vulnerable to increased threats from pests and disease due to climate change. The knowledge gained in these areas will allow partners to develop and recommend new IPM options to countercurrent threats and future potential challenges.

11.3.1.2 Food, Feed, and Environmental Safety

Pesticide residues, heavy metals, and microbial and mycotoxin contamination in food and animal feed are serious health risks. Aflatoxin, a toxin produced by fungi, is particularly dangerous to humans and animals, causing liver cancer, stunting, low weight, and high disease susceptibility. These contaminants also make it necessary to have stringent quality standards on food products, thus depriving the farmers and exporting countries of a vital income. The threat to food and feed safety is addressed by developing new varieties of crops with resistance to fungal colonization, reduced toxin production, and swifter toxin degradation. Scaling up and scaling out biological control will provide effective solutions to food and animal feed contamination. The development and application of cost-effective mycotoxin detection tools increases opportunities for exporting agricultural produce and allows for the mitigation of health risks from local food supplies. Developing alternatives to pesticides and increasing farmers' awareness and knowledge about the negative impacts of pesticides will enhance the benefits of existing and new crop health management technologies in this area.

11.3.1.3 Agroecosystem Resilience

High genetic crop and cropping system diversity, diversified landscape structures, and appropriate agricultural practices are important to maintain long-term agricultural productivity and sustainability. Relatively little research has been conducted to understand agroecosystem resiliencies and soil health as an approach to control pests. Conservation agriculture and the enhancement of natural enemies to keep pest populations under a control threshold are major elements of CHM. Ideally the agroecosystem is developed to function in a largely self-regulating manner to counteract a range of pests and diseases and to produce high yields of good quality with minimal impact on the environment. The use of companion cropping for the integrated management of soil fertility also forms an important part of CHM, enhancing agrobiodiversity and sustaining profitable agriculture. Diverse soil biota will not only help to prevent losses due to soilborne pests but also increase the rate at which organic matter and toxic compounds decompose and improve nutrient recycling and soil structure. The research institutes should focus on broadening the understanding of the ecological relationships in agricultural production systems to improve soil, root, and plant health in key regional or global cropping systems of the tropics and subtropics.

11.3.2 Innovations in CHM

The research institutes are already at the forefront of deploying genetic resources from their in-trust germplasm collections and advanced crop breeding populations for improving the resistance of crops to biotic and abiotic stresses. However, in many cases, inadequate or no sources of resistance have been found in established crop germplasm or wild relatives. Whereas IPM supports the effective use of resistance in crops, crop protection has to act independently where adequate host plant resistance does not exist to keep pests under control.

Assessing and improving the health of agroecosystems and their resilience against potential threats, such as water shortages, heat stress, and insect and fungal pressures, can be furthered by using advanced diagnostic tools that can detect changes in the functioning of plants and systems at multiple scales. Employing these tools should enable the more targeted and efficient application of any necessary CHM strategy, thereby ensuring its longevity and effectiveness. Such diagnostic technologies may be employed at the farm level, such as pest reporting synchronized via mobile phone messages or the precise assessment of soil health across farms. They may also be implemented on a much larger scale, as with the remote sensing of pest outbreaks or stresses.

The key to the successful implementation of any of the technologies highlighted will be their flexibility to integrate with and improve other aspects of the CHM strategy. It must be emphasized that enabling conditions have to be in place for farmers and food producers to take full advantage of these technologies.

11.3.2.1 Remote Sensing

The ability to accurately assess the health of agroecosystems is crucial to determining the need for and effects of any CHM strategy. Remote sensing is one emerging tool available to IPM for ecosystem surveillance. Remote sensing is a very flexible tool with the potential to offer new insights into crop health at temporal and spatial scales that would have required intensive human efforts in the past. Remote sensing has the potential to be an excellent tool for large-scale assessment and management of crop health. Different forms of spectral assessment are being used in predicting the development of disease prior to symptom expression, in crop breeding for the early detection of resistance, and for pest assessment in ecosystems.

11.3.2.2 Precision Crop Protection

Although this is often considered expensive and primarily useful for large farm operations, it is adaptable in developing countries with the necessary infrastructure and larger farm units. Precision technology can be used to accurately determine the presence and impact of pests on a crop in a particular field or part of a field. Pests can then be mapped to GPS coordinates to target the delivery of specific resistant varieties, biocontrol agents, or pesticides. Precision technology can have an impact in extensive production systems (i.e., for rice, maize, and wheat) where it allows the optimum use of inputs for CHM and crop productivity while reducing the need for large-scale sampling and extension input (Oerke et al. 2010). Many small farmers already practice a form of precision agriculture without any technological aides. They know the variability in their fields and try to use certain inputs on a refined scale. They are well positioned to improve if the information is made available on what to do, where, and when, in response to the needs of small but variable land plots.

11.3.2.3 Pest Risk Analysis

Understanding the shifts in pest range or the intensification of pest damage and predicting where adaptation measures may be required are key goals of any strategy to manage plant health in a region. Pest phenology modeling and risk mapping using Geographic Information Systems (GIS) (Sporleder et al. 2008) are innovative tools to assess and understand how pests may spread across regions. Process-based phenology models use a number of functions to describe temperature-driven processes, such as development, mortality, and reproduction in insect species. They produce full life-table parameters to predict key population parameters such as net reproduction rate, mean generation time, intrinsic and finite rate of increase, and doubling time. For an analysis in space of the risk of pests, generic risk indices (index for establishment, generation number, and activity index) can be visualized in GIS maps using advanced Insect Life Cycle Modeling tools and software (Sporleder et al. 2009).

11.3.2.4 Early Disease Diagnosis

Early detection of the appearance of diseases or their causal agents followed by rapid and accurate identification is essential if correct control measures are to be deployed. Nucleic acid sequencing and advances in DNA bar coding, microarray technologies, and lateral flow devices promise to revolutionize plant diagnostics in the near future (Boonham et al. 2008). DNA microarrays printed on the bottom of an Eppendorf, which can be read with a regular document scanner, have the capability to detect many pathogens simultaneously. Little training is required and thus the technology can be implemented in any laboratory without the need of specialized or expensive equipment. DNA bar coding, on the other hand, relies on the generic amplification and sequencing of a nucleic acid sequence that provides a “bar code” unique to any specific organism, enabling its rapid and precise identification. Infield methods for plant diagnostics are dominated by a single format: the serologically based lateral flow device (LFD). The “pregnancy kit” type LFDs are extremely robust and easy to use and interpret, but are limited to known pathogens for which antisera are available.

11.3.2.5 Cropland Management

The impact of new forms of cropland management on crop production, and especially on limited water resources, can lead to losses if this is not designed with pests in mind. Pests can bring greater reductions in crop water-use efficiency under poorly designed systems. New or modified crop and landscape management approaches such as “push and pull,” intercropping, relay and sequential planting, border strips, and living mulches can be used for the management of pests while simultaneously conserving water resources. The incorporation of living mulches is an example of an innovative cropping system for integrated soil and pest management in cereal-based farming systems, minimizing pest infestation, sustaining permanent soil cover, and increasing soil fertility (Chabi-Olaye et al. 2005). Similarly, the intercropping of trees and coffee with banana can alter pest pressure and spread (Staver et al. 2001). Intercropping and mulching are effective in the management of soilborne pests in perennial crops, by stimulating beneficial microorganisms that regulate densities of pests such as plant parasitic nematodes (Pattison et al. 2003).

11.3.2.6 Seed/Seedling/Seedbed Treatment

Seeds coated with chemical or biological agents protect plants from a wide range of pests and diseases in the early stages of growth, ensuring a good establishment and higher yield. Seed treatments also reduce the risk of farmers and the environment being exposed to pesticides. Advances have been made in coating maize seeds with herbicides (Kanampiu et al. 2002) and sorghum seeds with the mycoherbicide *Fusarium oxysporum* f. sp. *strigae* (Elzein et al. 2006) to combat the parasitic weed *Striga hermonthica*. Bacterial seed treatment to control soilborne pests is marketed in many countries, both the developed and the developing (Hallmann et al. 2009). The use of mutualistic fungal endophytes to manage pests and enhance plant tolerance is being tested in bananas, rice, vegetables, and ornamentals (Hallmann et al. 2009). Rhizobacterial treatment of potato and rice is also considered practical (Padgham and Sikora 2007) for pest management. The development of beneficial microorganisms as a component of seed, seedbed, and seedling treatment technology is moving forward quickly in many countries and could benefit developing countries in the near future. Partnerships with the private sector are crucial when the newest technologies are to be adapted to the needs of small-scale farmers and ensure the structures are in place through which they receive high-quality seeds and seedlings that remain protected when placed in the hostile agro-ecosystem environment (Dubois et al. 2006).

11.3.2.7 Semiochemicals

Semiochemicals control the communication of insects both interspecific (allelochemicals) and intraspecific (pheromones). They are used in pest management either alone for pest monitoring and decision-making and for mass trapping or mating disruption or in combination with insecticides, sterilants, or insect pathogens, the so-called “attract-and-kill” strategy (El-Sayed et al. 2009). Additionally, semiochemicals released by plants can repel insect pests from the crop (“push”) and attract them into trap crops (“pull”). In this way the push–pull approach has been developed for controlling insect pests and the parasitic weed *Striga hermonthica* for subsistence farming systems in Africa and has been adopted by over 25,000 maize smallholder farmers in East Africa. There, maize yields have subsequently increased from about 1 t/ha to 3.5 t/ha with minimal inputs (Khan et al. 2008). The potential use of semiochemicals for pest management on small-scale farms in developed countries remains underexploited. Similarly, a clearer understanding of the behavior of insects, including their migration capacities and spatial dispersal, could enable simple systems of pest management to be developed (Kroschel et al. 2009).

11.3.2.8 Genetically Modified Crops with Multiple Pest Resistance

1. *GM potato resistant to Colorado beetle (CPB) and virus Y (PVY):* The Monsanto Company developed NewLeaf Y potato lines SEMT15-02, SEMT15-15, and RBMT15-101 through a specific genetic modification of cultivars Shepody and Russet Burbank to resist infection by PVY and to feeding by the CPB. To develop these potatoes, the Cry3A gene isolated from a naturally occurring soil bacterial strain *Bacillus thuringiensis* subsp. *tenebrionis* was supplemented with the PVYcp gene isolated from a naturally occurring strain of PVY.
2. *GM potato resistant to Colorado beetle (CPB) and leaf roll virus (PLRV):* The Monsanto Company has developed the NewLeaf Plus potato varieties that are resistant to infection by PLRV and to feeding by the CPB (Lawson et al. 2001). To develop these potatoes, select clones of the Russet Burbank potato variety were supplemented with the Cry3A gene isolated from a naturally occurring soil bacterium *B. thuringiensis* subsp. *tenebrionis* and the PLRVrep gene isolated from a naturally occurring strain of the potato leaf roll virus.
3. *GM rice resistant to stem borer, sheath, and bacterial blight:* The Xa21 gene (resistance to bacterial blight), the Bt fusion gene (for insect resistance), and the chitinase gene (for tolerance of sheath blight) were combined in a single rice line by reciprocal crossing of two transgenic homozygous IR72 lines. The identified F4 plant lines, when exposed to infection caused by *Xanthomonas oryzae* pv. *oryzae*, showed resistance to bacterial blight. Neonate larval mortality rates of yellow stem borer (*Scirpophaga incertulas*) in an insect bioassay of the same identified lines were 100 %. The identified line pyramided with different genes to protect against yield loss showed high tolerance of sheath blight disease caused by *Rhizoctonia solani* (Datta et al. 2002).
4. *Combined resistance to stem borer and herbicide glufosinate in rice:* A stacked combination of Bt toxins Cry1Ab and Cry1Ac along with tolerance to the herbicide glufosinate (*bar* gene) was created in order to serve as a parental line for generating hybrid rice varieties. The resultant transgenic line was resistant to stem borer insects and to the herbicide glufosinate.
5. *Insect-protected corn stacked with Roundup Ready:* Maize has varieties that are either stand-alone glyphosate resistant (GR) varieties or varieties that combine GR and transgenic Bt (*B. thuringiensis* toxin) traits for insect resistance. Table 11.3 lists and describes the insect-protected corn stacked with Roundup Ready Corn.
6. *Insect-protected corn stacked with LibertyLink:* Table 11.4 lists and describes the insect-protected corn stacked with LibertyLink Corn.
7. *Insect-protected corn stacked with Roundup Ready and LibertyLink:* Table 11.5 lists and describes the insect-protected corn stacked with Roundup Ready and LibertyLink.

11.4 Policies Enabling/Inhibiting Crop Health Management

For CHM, a conducive policy environment is needed in addition to access to the knowledge of biotic and abiotic factors with an impact on the cropping system and to the tools available for farmers to make correct agronomic and IPM decisions.

11.4.1 The Convention on Biological Diversity: A Significant Obstacle

The Convention on Biological Diversity (CBD) has proven a major influence on the biological control of pests and on ecosystem resilience. The exchange of beneficial plants and biocontrol agents between countries has become increasingly difficult. In several instances, the transfer of potentially important living organisms has been

Table 11.3 Corn varieties with combined resistance to insect pests and glyphosate herbicides

Product registrant trade name	Characteristic	Event
Monsanto YieldGard Corn Borer with Roundup Ready Corn 2	Cry1Ab, European and Southwestern corn borers, sugarcane borer, and Southern cornstalk borer protection	Mon 810+NK603
	Glyphosate herbicide tolerance	
Monsanto YieldGard Rootworm with Roundup Ready Corn 2	Cry3Bb1, Western, Northern, and Mexican corn rootworm protection	Mon 863+NK603
	Glyphosate herbicide tolerance	
Monsanto YieldGard Rootworm	Cry3Bb1, Western, Northern, and Mexican corn rootworm protection	Mon 863
	Glyphosate herbicide tolerance	
Monsanto YieldGard Plus with Roundup Ready Corn 2	Cry1Ab, Cry3Bb1, European and Southwestern corn borers, sugarcane borer, Southern cornstalk borer, and Western, Northern, and Mexican corn rootworm protection	Mon 810+Mon 863+NK 603
	Glyphosate herbicide tolerance	
Monsanto YieldGard VT Rootworm/RR2	Cry3Bb1, Western, Northern, and Mexican corn rootworm protection	Mon 88017
	Glyphosate herbicide tolerance	
Monsanto YieldGard VT Triple	Cry1Ab, Cry3Bb1, European and Southwestern corn borer, sugarcane borer, Southern cornstalk borer, and Western, Northern, and Mexican corn rootworm protection	Mon 810+Mon 88017
	Glyphosate herbicide tolerance	
Syngenta GT/RW	Modified Cry3A, Western, Northern, and Mexican corn rootworm protection	MIR60+SYTGA 21
	Glyphosate herbicide tolerance	
Monsanto Genuity VT Double PRO	Cry1A.105, Cry2Ab2, European and Southwestern corn borers, sugarcane borer, Southern cornstalk borer, corn earworm, and fall armyworm protection	Mon 89034+ NK603
	Glyphosate herbicide tolerance	
Monsanto Genuity VT Triple PRO	Cry1A.105, Cry2Ab2, Cry3Bb1, European and Southwestern corn borers, sugarcane borer, Southern cornstalk borer, corn earworm, fall armyworm, Western corn rootworm, Northern corn rootworm, and Mexican corn rootworm protection	Mon 88017+Mon 89034
	Glyphosate herbicide tolerance	

refused, hindering the environmentally sound work conducted under IPM to find alternatives to pesticides. A background study by FAO (Cock et al. 2009) and other publications highlighted the needs of the biocontrol community and presented a number of case studies of successful work and hindrance through CBD.

The International Regime on ABS is expected to be adopted in October 2010 by the 193 member countries of the CBD, but its implementation and practicability remain unclear. Currently, ABS seems to constitute a significant obstacle for agricultural research in general and breeding and pest control in particular. It is therefore necessary that the ABS Protocol provides room for specialized ABS arrangements for genetic resources, such as ubiquitous beneficial microorganisms for which the application of the CBD's concept of country of origin is doubtful, but which are of direct relevance to future pest management strategies imposed by climate change and intensified farming systems (SGRP 2010).

Table 11.4 Corn varieties with combined resistance to insect pests and glufosinate herbicides

Product registrant trade name	Characteristic	Event
Syngenta Agrisure CB/LL	Cry1Ab, corn borer protection	Bt11
	Glufosinate herbicide tolerance	
Dow AgroSciences Pioneer Hi-Bred Herculex I	Cry1F, Western bean cutworm, corn borer, black cutworm and fall armyworm resistance	TC1507
	Glufosinate herbicide tolerance	
Dow AgroSciences Pioneer Hi-Bred Herculex RW	Cry34/35Ab1, Western corn rootworm, Northern corn rootworm protection	DAS-59122-7
	Glufosinate herbicide tolerance	
Dow AgroSciences Pioneer Hi-Bred Herculex Xtra	Cry1F, Western bean cutworm, corn borer, black cutworm and fall armyworm, Northern corn rootworm, Western corn rootworm protection	TC1507+DAS 59122-7
	Glufosinate herbicide tolerance	
Syngenta Agrisure CB/LL/RW	Cry1Ab, corn borer protection. Modified Cry3A, protection of Western, Northern, and Mexican corn rootworm protection	Bt11+MIR604
	Glufosinate herbicide tolerance	
Syngenta Agrisure 3000GT	Cry1Ab, corn borer protection. Modified Cry3A, Western, Northern, and Mexican corn rootworm protection	SYTGA 21+Bt 11+MIR604
	Glufosinate herbicide tolerance	

Table 11.5 Corn varieties with combined resistance to insect pests, glyphosate, and glufosinate herbicides

Product registrant trade name	Characteristics	Event
Dow AgroSciences Pioneer Hi-Bred Herculex I	Cry1F, Western bean cutworm, corn borer, black cutworm, and fall armyworm resistance	TC1507+NK603
Monsanto Roundup Ready Corn 2	Glyphosate herbicide tolerance	
	Glufosinate herbicide tolerance	
Syngenta Agrisure GT/CB/LL	Cry1Ab, corn borer protection	SYTGA21+Bt11
	Glyphosate herbicide tolerance	
	Glufosinate herbicide tolerance	
Dow AgroSciences Pioneer Hi-Bred Herculex RW	Cry34/35Ab1, Western corn rootworm, Northern corn rootworm protection	DAS-59122-7+NK603
Monsanto Roundup Ready Corn 2	Glufosinate herbicide tolerance	
	Glyphosate herbicide tolerance	
Monsanto GenuitySmart-Stax Dow AgroSciences SmartStax	Cry1A.105; Cry2Ab2; Cry1F; Cry3Bb1; Cry34/35Ab1; Western, Northern, and Mexican corn rootworms; European and Southwestern corn borers; sugarcane borer; Southern cornstalk borer; Western bean and black cutworms; corn earworm; and fall armyworm protection	Mon88017+ Mon89034+ TC1507+DAS59122-7
	Glyphosate herbicide tolerance	
	Glufosinate herbicide tolerance	

11.4.2 Reformed Knowledge Transfer to Support IPM

Pest management structures and policies need to recognize that crop health is an essential element of sustainable agriculture that needs immediate improvement. Many policies are aimed at supporting pest control as a separate activity, often relying solely on the application of pesticides or the use of resistant cultivars. In the longer term, this has been shown to be unsustainable – whether as a result of pests overcoming host plant resistance and building up resistance to pesticides or the improper, excessive, or unnecessary use of pesticides with unacceptable impacts on humans, animals, and ecosystem services.

Farming has replaced diverse ecosystems with simplified cropping systems that have disruptive impacts on the services that an intact natural ecosystem provides. Therefore, a sole reliance on ecosystem services for CHM is insufficient. When pest outbreaks and devastating crop losses occur, farmers become disillusioned with the effectiveness of complex approaches for CHM and often revert to the sole use of pesticides. This underscores the need for integrating modern and traditional pest management approaches that provide appropriate tools and solutions for different situations. Structures and policies must provide incentives to adopt practices that favor ecosystem services. These policies must support extension officers and farmers in incorporating the range of options available and the positive and negative effects they carry, when not used by the farmer. Policies are needed that facilitate the development of effective and environmentally sound management technologies, as well as practices that can be made readily available to the farmers. Policy makers need to provide incentives to encourage the adoption and adaptation of IPM to local conditions through a strengthening of knowledge transfer to upgraded extension services.

Extension, the link between science and the farmer and the backbone of sustainable crop improvement, needs to be a major aspect of CHM in the future. Extension is the only effective way of promoting IPM, but in many developing countries, budget cuts and a lack of emphasis on agricultural development have left farmer–extension ratios far too large for adequate advice to be provided. This causes farmers to shift towards the promises of local pesticide salespersons when they encounter a serious pest or disease problem. Policies need to be put in place to strengthen and reform governmental and nongovernmental extension services and to promote coordination and cooperation between the public, private, and not-for-profit sectors. The public and private sectors need to be trained and rewarded for the promotion of IPM principles. For local pesticide retailers and dealers, this should include training programs, certification, and monitoring schemes. These activities have to be supported by a stricter international control of the sale of cheap, fake, and internationally banned pesticides.

However, traditional linear research-extension models alone are unlikely to be successful in scaling out multicomponent IPM technologies. There is a need for a shift away from the promotion of pure technology towards innovation systems. These include functioning networks of farmers, technology developers, extension workers, local businessmen, and researchers and facilitate the adaptation of technologies to local conditions and farmers' decision-making on the selection and deployment of technologies in their time and place.

There is also a dire need for the introduction and adaptation of modern extension tools, such as online-decision-support systems to increase the impact of extension. These innovative systems are used in practical IPM in developed countries and can be modified to suit specific regions and cropping systems. Pest monitoring models and standard recommendations for a range of pests affecting a broad spectrum of crops based on weather data can be used to make CHM decisions in the field. This can be done centrally and the information on management can be spread by telecommunication tools to extension agents and farmers. However, these modern methods should be applied in such a way that they help farmers to make more informed decisions, rather than trying to convince them to use a specific technology.

Mass media information campaigns and entertainment education enhance traditional extension approaches by making a large audience aware of the issue at the most appropriate times (Huan et al. 2008). Whatever dissemination approaches are being used, there is a need for follow-up programs to sustain adoption. At the same time, information must flow both ways. An understanding of why farmers in different areas adopt certain practices or technologies, their sociological perspectives, language, culture, market principles, and decision-making necessitates the involvement of more than just experts on specific technologies or agronomic disciplines. Most research currently available focuses on either the benefits or the risks of different practices. There needs to be a holistic approach, considering all benefits and risks – including externalities and mechanisms of how these can be achieved.

11.4.3 Incentives to Adopt New CHM Technologies

Farmers adopt new practices if they are profitable and if they improve yield. A major incentive to adoption is the demonstration that a technology is profitable. This requires that "income distorting" subsidies on specific pest control options, such as chemical pesticides, should be replaced by educational programs on CHM and the properly integrated use of IPM inputs. In addition to training, monetary incentives promote the adoption of sustainable CHM practices.

Improved crop health is a public environmental good where local individual actions benefit a large community. The potential impact of adjusted policies that provide payments for environmental services to farmers for practicing CHM and encourage the use of environmentally friendly approaches with safer pesticides should be evaluated and subsequent measures taken.

11.5 Capacity Building

11.5.1 The Problem

Without sound human capacity to develop, adapt, understand, and apply CHM, crop losses will continue to be a major contributor to food insecurity. The multifaceted nature of CHM and the many scientific and technological progresses made require training and capacity development at many levels, from policy makers to national researchers, knowledge brokers, extension agents, and finally farmers.

Most higher education institutions in developing countries do not offer inclusive courses in crop protection. Future scientists working in CHM are poorly trained in all relevant disciplines during their university careers. This lack of training cascades through the educational system, also affecting technical agricultural institutions and their practical agricultural curricula. If we are to make an impact on food security in the coming 15 years, we have to strengthen the next generation in IPM expertise.

11.5.2 The Solution

A system-wide capacity building program in CHM needs to be developed. To make such an impact, policy makers, leaders of agricultural ministries, heads of university crop protection institutes, and leaders in extension need to be exposed to the true nature and scale of the pest and contaminant problems. In some cases, it will be necessary to retool the solutions available to solve crop health problems in the near future.

The following three capacity building programs are proposed, the first two to rotate among Africa, Asia, and South America and the third to be implemented everywhere.

11.5.2.1 Implementation of a Rotational Advanced Knowledge Exchange Program

The advanced national and international research and education institutes as well as private industry need to develop a short but intensive training program for key national scientists, research managers, scientific staff, and political decision-makers to expose them to the negative impacts that pests and toxic contaminants are having on human and environmental health, food security, and trade. The course would tackle mycotoxins, pesticide residues, and microbial contamination. It would present the technologies that are already available or currently under development that could be of enormous benefit to their countries if the right policies and institutional infrastructure are in place and if the scientists are properly trained.

This course would be implemented in different regions of the world by the agricultural universities/research institutes. IPM scientists in the other regions, as well as researchers at advanced institutes and representatives from the private sector, would backstop and present together the latest solutions to crop health problems across crops of the relevant food baskets and eco-regions.

11.5.2.2 Implementation of an Advanced Studies Program

As above, the advanced national and international research and education institutes and the private sector would develop the structure for intensive advanced training courses for key national scientists, research managers, and extension experts to upgrade their expertise in the latest technologies available to enhance plant health across ecosystems and across the crops in the food basket of the growing region. It would also focus on the preservation of the gained knowledge.

By means of modern and affordable concepts of information technology, the participants in the program would be enabled to document their experiences in an easy and straightforward manner. Through the Internet, this knowledge can be made readily accessible to others within and outside the program and thus preserve the program's results, even when participants leave or move on to other positions. The basic course would then be fine-tuned by the agricultural universities/research institutes hosting the course to customize it to specific regional contexts. These would be conducted in the three major regions (sub-Saharan Africa, South Asia, and Central Asia) affected by food shortages, malnutrition, contaminants in the food chain, and climate change. The technologies presented would be selected to fit the problems, cropping systems, and food basket crops in the specific region where the course is offered. Staff from all of the advanced national and international research and educational institutes would backstop as needed, so that all relevant technologies could be presented and the contents of the course could be collaboratively and continuously refined.

Both the knowledge exchange and the advanced studies programs would be automatically upgraded as experience is gained. The programs could be moved to the E-learning mode for further distribution.

11.5.2.3 Implementation of a Masters' Program in IPM and Overall Crop Health

The concept would be to develop a sandwich (split-location) degree program with preference for extension agents and crop protection advisers. The goal is to develop highly qualified experts who have a real interest in extension and problem solving. This type of program does not exist in the developing world at this time. It is a weak link, but it is the key to the success of sustainable crop production. Training programs conducted outside the region usually lead to the training of students not necessarily interested in extension or of students who remain in the developed world to build their careers.

The 27-year-old African Regional Postgraduate Programme in Insect Science (ARPPIS) at ICIPE, extending to 34 African universities, stands as an example for such a program based in Africa. The Masters program in IPM would include a number of satellite universities from different countries based in a region. The national professors working in crop protection would be part of the core of the teaching and training program. The curriculum would be developed by the national program leaders together with CGIAR's training personnel and public and private institutes of higher learning. The program would target a major weakness in current food production: the lack of well-trained extension specialists. At the same time, it would upgrade national university programs in crop protection, a precondition for sustainability in food production. It would be economical in that the students will remain in their region and are not shipped around the world to centers of excellence in training in temperate regions. They would remain part of the online information-sharing network after graduation.

The ultimate goal of the capacity building programs is to solve crop health problems by educating the people who are in a position to make an impact on sustainable food production. This will be accomplished by placing CHM in the knowledge chain from the policy maker, through the researcher and extension expert, to the farmer.

11.6 Collaboration and Partnerships to Improve Crop Health Management

The multidisciplinary nature of sound CHM requires inclusive partnerships for development, adaptation, and adoption. Potential collaborations and partnerships that should be considered in this systems approach are farmers and farmers' associations, then on partners who are in direct contact with farmers, and finally on partners who influence technology or provide the enabling environment for change from component-based technologies towards a holistic agricultural paradigm.

These partners must make possible the capacity building by farmers through extension educators, input suppliers, and others. This clearly requires policy makers, regulatory agencies, and financial managers to provide an enabling environment to allow for new markets, market structures, transportation infrastructures, finance, and new IPM tools for plant health. Such an enabling environment will provide incentives for farmers to use new inputs (healthy seeds of new cultivars and crops, biological control agents, safer pesticides, pest monitoring and scouting tools, etc.). It will take advantage of new market opportunities for new crops or those meeting specific quality or pesticide residue standards – all factors that will address food security, sustainability, and poverty reduction. It is important to understand that the benefits are not just for farmers and their suppliers; the ultimate beneficiary is the consumer in both local and export markets.

Critical to the successful development of a holistic CHM paradigm is participatory project planning involving as many as possible of the partners. Such participatory planning will ensure that partners hold project ownership: they have all agreed on the objectives and proposed goals and outputs, activities, and budget needs. Identification of initial project sites, documentation of the baseline situation, provision for project monitoring, impact assessment, and publicity are all critical to successful planning. The importance of planning grants to bring these diverse partners together cannot be overemphasized.

Prior to the initial planning meeting with the partners, preparatory work with stakeholders is very important to build a critical mass for participation in and commitment to the potential project. Publicity is critical to transferring successes and to inspiring others to duplicate or adopt CHM in new locations and to generate new support from donors or other financiers to promote plant health. Finally, partners in each project should develop plans for succession planning and mechanisms for sustaining the projects beyond initial funding. It is both logical and practical that the advanced national and international research and education institutes should take the leadership in initiation since they are strategically located worldwide, have the research and extension faculty expertise, and possess established networks to initiate collaboration. This will, however, require the advanced national and international research and education institutes and their faculties to cooperate across disciplinary and geographic lines, both internally and with other organizations involved in international agriculture.

The benefits from recognizing the diverse partners in CHM and the need for them to collaborate in project planning, implementation, and evaluation will be seen in the delivery and adoption of improved crop, soil health, improved incomes, and improvements in a diversity of environmental indicators. The inclusive participatory planning, implementation, and evaluation process should result in improved cooperation and trust between partners and donors. As a result, many synergies between partners, both foreseen and unforeseen, will be realized. At the same time, linkages and networks will begin to develop for future rural development initiatives.

11.7 Conclusions

The advanced national and international research and education institutes have the capacity and capability to adopt a balanced multidisciplinary approach, and they have made efforts in this direction in the past. Securing the long-term funding for CHM would allow scientists to intensify inter-center and other forms of collaboration and in harnessing synergies better for more serious impacts on the big problems, such as food security, sustainability, and poverty reduction.

Substantial increases in food production can be attained relatively quickly by upgrading CHM strategies. However, this requires adequate financial investment in measures that reduce yield losses now. Investment only in new technologies targeted at increasing potential yields ignores the fact that significant losses are occurring now from weeds, animal pests, and diseases and that these can be reduced.

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Climate Change Adaptation

12

Abstract

There is a need to improve and promote existing management strategies for dealing with climate variability. This will enhance farmers' capacity to plan for, and deal with, extreme events (droughts, floods, fire, hail, etc.) in the medium and longer term. Using climate forecasts at a range of time scales to make preemptive, tactical management adjustments will help to track the early stages of climate change, until the longer-term trends and necessary adaptations in particular regions become clearer.

It is important to note that many climate adaptation options are similar to existing "best practice" and good natural resource management and do not require farmers to make radical changes to their operations and industries in the near term. These options can, and should, be prioritized as part of a "no regrets" or win–win strategy for agriculture because they will provide immediate and ongoing benefits, as well as prepare the sector for climate change.

Information delivery to farmers from climate analyses can be enhanced by providing projections of management and policy-relevant weather metrics (e.g., cold indices for stone fruit), providing climate information at scales relevant to the decisions being made, and combining information on both climate variability and trends in seasonal and medium-term (decadal) forecasts. Biotechnology and traditional plant and animal breeding have the potential to develop new "climate-ready" varieties and new crops or pastures preadapted to future climates. Plant nutrition can be adjusted by measures such as precision fertilizer use, legume rotations, and varietal selection to maintain the quality of grain, fruit, fiber, and forage sources. Irrigation efficiency will become critical as water resources become more constrained. This can be assisted by identifying less water-intensive production options, by developing better water delivery technologies, and by implementing water markets and water-sharing arrangements. Soil and water conservation methods and new systems become even more important as climates fluctuate more and extreme events become more frequent. Biosecurity, quarantine, monitoring, and control measures can be strengthened to control the spread of pests, weeds, and diseases under a warming

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climate. Better models of agricultural systems can assess climate change impacts and more reliably explore and improve adaptation options. Monitoring and evaluation systems are needed to track changes in climate, impacts on agriculture, and the effectiveness of adaptation measures, to help decide when to implement particular options and to refine them over time. Policy and management decisions require timely inclusion of climate information as it becomes available, as well as closer collaboration between policy makers, managers, researchers, extension agencies, and farmers.

Keywords

Improved crop seeds • Livestock and fish cultures • Crop production adaptation • Water adaptation • Agro-forestry • Pest management • Livestock adaptation • Energy adaptation • Early warning systems • Crop insurance schemes • Livelihood diversification • Access to information

Adaptation is defined as a response to actual or expected climate stimuli or their effects, which moderates harm or exploits beneficial opportunities. In human systems, adaptation can be both anticipatory and reactive and can be implemented by public or private actors (UNDP 2007/2008).

Adaptation refers to efforts by society or ecosystems to prepare for or adjust to future climate change. These adjustments can be protective (i.e., guarding against negative impacts of climate change) or opportunistic (i.e., taking advantage of any beneficial effects of climate change). Adaptation is changing activities and processes in order to lessen negative impacts of climate change that is already taking place, and to open the agricultural sector to new opportunities that might arise from a changing climate.

Historically agriculture has shown a considerable ability to adapt to changing climatic conditions, whether these have stemmed from alterations in resource availability, technology, or economics. Many adaptations occur autonomously and without the need for conscious response by farmers and agricultural planners (Brooks et al. 2013).

To deal with the impact of climate change, the potential adaptation strategies are: developing cultivars tolerant to heat and salinity stress and resistant to flood and drought, modifying crop management practices, improving water management, adopting new farm techniques such as resource-conserving technologies (RCTs), crop diversification, improving pest management, better weather forecasting and crop insurance, and harnessing the indigenous technical knowledge of farmers.

Easterling et al. (2007) describe a range of options, at the level of autonomous adaptation, for cropping and livestock systems:

- Use of different varieties or species with greater resistance to heat or water stress, or adapted phenology (maturation times and responses)
- New cropping practices, including adjustments in timing and locality of crop production, and changed water and fertilizer management to maintain yield quality and quantity
- Greater use of water conservation technologies, including those to harvest water and conserve soil moisture, or, in flood-prone areas, water management to prevent water logging, erosion, and nutrient leaching
- Diversification of on-farm activities and enhancement of agrobiodiversity, with greater integration between livestock and cropping systems
- Adapted livestock and pasture management, including rematching stocking rates and timing with pasture production, new varieties and species of forage and livestock, updated fertilizer applications, and using supplementary feeds and concentrates

- Improved management of pests, diseases and weeds, for example, through integrated pest management, new crop and livestock varieties, improved quarantine, and sentinel monitoring programs.
- Better use of short-term and seasonal climate forecasting to reduce production risk

12.1 Improved Crop Seeds, Livestock, and Fish Cultures

12.1.1 Key Issues

- Promoting use of biotechnology
- Research and promotion of C4 pathways in C3 plants
- Conserving indigenous genetic resources
- Management and dissemination of improved varieties
- Conserving "Agricultural Heritage"

The introduction of new cultivated species and improved varieties of crop is a technology aimed at enhancing plant productivity, quality, health and nutritional value, and/or building crop resilience to diseases, pest organisms, and environmental stresses. The use of the appropriate crop varieties reduce their vulnerability to risks associated with climate change (e.g., harvest losses due to pests, diseases, or droughts) and improve their livelihoods.

The traits that may be important for climate change adaptation include:

- Capacity to tolerate high temperatures and droughts
- Fire resistance and tolerance, especially for trees
- Resistance or tolerance to diseases and pests
- Phenotypic plasticity

Breeding new and improved crop varieties enhances the resistance of plants to a variety of stresses that could result from climate change. These potential stresses include water and heat stress, water salinity, and the emergence of new pests. Varieties that are developed to resist these conditions will help to ensure that agricultural production can continue and even improve despite uncertainties about future impacts of climate change. Varieties with improved nutritional content can provide benefits for animals and humans alike, reducing vulnerability to illness and improving overall health.

12.1.2 Advantages

The process of farmer experimentation and the subsequent introduction of adapted and accepted varieties can potentially strengthen farmers' cropping systems by increasing yields, improving drought resilience, boosting resistance to pests and diseases, and also by capturing new market opportunities. To make the products of the research process more relevant to the needs of smallholder farmers, research organizations are increasingly engaged in participatory research in recognition of its potential contribution to marginal areas with low agricultural potential. There is a need to identify crops and varieties that are suited to a multitude of environments and farmer preferences. Participatory approaches increase the validity, accuracy, and particularly the efficiency of the research process and its outputs. Researchers are better informed and can better inform about the traits that should be incorporated in improved varieties. Participatory processes also enhance farmers' capacity to seek information, strengthen social organization, and experiment with different crop varieties and management practices.

12.1.3 Disadvantages

Farmer experimentation using only native varieties can limit the range of benefits and responses that may be found among the materials being tested, although local adaptation and acceptance are ensured. At the same time, problems can arise with the introduction of exotic species (from other origin centers) that after being introduced turned into pests. There are several examples of introduced species that have escaped control becoming pests or agricultural weeds.

12.1.4 Developing Climate-Ready Crops

Development of new crop varieties with higher yield potential and resistance to multiple stresses (drought, flood, salinity) will be the key to maintain yield stability. Improvement in germplasm of important crops for heat-stress tolerance should be one of the targets of breeding program. Similarly, it is essential to develop tolerance to multiple abiotic stresses as they occur in nature. The abiotic stress tolerance mechanisms are quantitative traits in plants. Germplasm with greater oxidative stress tolerance may be exploited as oxidative stress tolerance is one example where plant's defense mechanism targets several abiotic stresses. Similar to the research efforts on conversion of rice from C3 to C4 crop, steps should be taken for improvement in radiation-use efficiency of other crops as well. Improvement in water-use and nitrogen-use efficiencies is being attempted since long. These efforts assume more relevance in the climate change scenarios as water resources for agriculture are likely to dwindle in future. Nitrogen-use efficiency may be reduced under the climate change scenarios because of high temperatures and heavy precipitation events causing volatilization and leaching losses. Apart from this, for exploiting the beneficial effects of elevated CO_2 concentrations, crop demand for nitrogen is likely to increase. Thus, it is important to improve the root efficiency for mining the water and absorption of nutrients. Exploitation of genetic engineering for 'gene pyramiding' has become essential to pool all the desirable traits in one plant to get the 'ideal plant type' which may also be 'adverse climate-tolerant' genotype.

Farmers need to be provided with cultivars with a broad genetic base. Their adaptation process could be strengthened with availability of new varieties having tolerance to drought, heat, and salinity and thus minimize the risks of climatic aberrations. Similarly, development of varieties is required to offset the emerging problems of shortening of growing season and other vagaries of production environment. Farmers could better stabilize their production system with basket of technological options.

12.1.5 Drought-Tolerant Varieties

Different agronomic adaptation practices are applicable to different farming systems and agroclimatic zones, including drought tolerance for adaptation to climate change. Many research institutions have developed various crop varieties suitable for specific climatic zones. For instance, new rice varieties with acceptable grain quality and yield and shorter growing duration need to be developed or introduced into rice-growing areas. The adoption of direct seeding pre-germinated seed, either by broadcasting or drum seeding, into flooded paddy fields can reduce the crop cycle by 10–45 days. Farmers need to be linked to leading research institutions to get certified seeds to increase production under changing rainfall regimes.

Fifty new maize hybrids and open-pollinated maize varieties have been developed and provided to seed companies and NGOs for dissemination, and several of them have reached farmers' fields. These drought-tolerant maize varieties produce 20–50 % higher yields than other maize varieties under drought conditions. Farmers choose their crops according to the climate in which they operate. For example, in Sahelian West Africa, farmers prefer drought-tolerant crops such as sorghum and cowpea (Kurukulasuriya and Mendelsohn 2006). Moreover, introduction of improved crop varieties should consider the local community's eating habits, cultural practices, agroecological conditions, and markets.

Several horticultural crop varieties have been released which are resistant to abiotic stresses such as heat and moisture (Table 12.1).

12.1.6 Promoting Use of Biotechnology

Biotechnology is an important tool for the development of genetic resources with greater adaptive capacity to cope with changing environments. It has huge potential for combating vulnerabilities in crops, livestock, and fisheries. Research and promotion of higher carbon (C4) pathways in low carbon (C3) plants and genetic

Table 12.1 Horticultural crop varieties resistant to major abiotic stresses

Vegetable crop	Abiotic stress	Resistant varieties
Tomato	Moisture	Arka Meghali
	Hot set	Pusa Hybrid-1
	Hot and cold set	Pusa Sadabahar
Chili	Moisture	Arka Lohit
Field bean	Moisture	Arka Jay, Arka Vijay, Konkan Bushan
Cowpea	Moisture	Arka Garima
French bean	Heat tolerant	Arka Komal
Cluster bean	Moisture	Pusa Nav Bahar, Pusa Sadabahar
Lima bean	Moisture	IIHR Sel-1, IIHR Sel-4
Round melon	Heat tolerant	Arka Tinda, Punjab Tinda
Long melon	Heat tolerant	Arka Sheetal, Punjab Long Melon
Bottle gourd	Heat tolerant	Pusa Summer Prolific Long
Bitter gourd	Heat tolerant	Pusa Do Mousami, Kalyan Sona
	Warm humid climate	Arka Harit, Coimbatore Long, Konkan Tara, Priya, CO-1, MC-84, MDU-3
Cabbage	High temp. tolerant	Pusa Ageti
Cauliflower	Curd development in May in lower hills	Pusa Him Jyoti
Turnip	Hot and humid climate	Pusa Sweta
Radish	High temp. tolerant	Pusa Chetki
Carrot	Temperate type, bolting, and seed setting under high temp.	Pusa Meghali
Palak	Not bolting in plains	Pusa Harit
Turmeric	Tolerant to drought	CO-1, BSR-1

manipulation of enzymes such as RuBisCo would help in increasing effectiveness of use of CO_2 and thus helping the reduction in GHG emissions.

DroughtGard maize will be the first commercially available transgenic (GM) drought-tolerant crop if it is released in 2013 as planned. Hybrid seed sold under this trademark will combine a novel transgenic trait (based on the bacterial *cspB* gene) with the best of Monsanto's conventional breeding program. The best performing lines of *cspA* and *cspB* showed yield increases of 30.8 % and 20.4 %, respectively. The best two *cspB* lines (CspB-Zm events 1 and 2) also showed significant gains in leaf growth, chlorophyll content, and photosynthetic rates. Non-transgenic controls suffered 50 % or 30–40 % yield losses under the two drought stresses (well-watered, drought immediately preceding flowering, drought during grain fill), respectively. Thus, the *cspB* gene appeared capable of minimizing kernel abortion, an irreversible (and therefore very important) component of yield loss under drought (Fig. 12.1).

Overexpression of *AVP1* in cotton not only improved drought and salt tolerance under greenhouse conditions but also increased fiber yield in dryland field conditions. The increased yield by *AVP1*-expressing cotton plants is due to more bolls produced, which in turn is due to larger shoot system that *AVP1*-expressing cotton plants develop under saline or drought conditions. The larger root systems of *AVP1*-expressing cotton plants under saline and water-deficit conditions allow transgenic plants access to more of the soil profile and available soil water, resulting in increased biomass production and yield (Fig. 12.2) (Pasapula et al. 2011).

The HRD gene in transgenic rice has improved water-use efficiency and the ratio of biomass produced to the amount of water used, through enhanced photosynthesis and reduced transpiration. Correlation of drought tolerance with root architecture (spread, depth, and volume) has been examined in cowpea (South Africa, West Africa, and India), rice (India), and beans (Central and South America). Other modifications are further from commercialization (Table 12.2).

12.1.7 Interventions

12.1.7.1 Research and Development

- Development of plant genetic resources to combat changing environments with special focus on plant physiological processes such as flowering, seed development, photosynthesis, respiration, water retentions, and plant growth regulation

Fig. 12.1 Monsanto's drought-resistant corn, at *right*, was tested next to traditional corn plants on the *left* (drought-aborted kernels)

Fig. 12.2 Field performances of cotton plants. (*Left*) Phenotypes of segregated non-transgenic line, (*Right*) Phenotypes of AVP1-transgenic line

Table 12.2 Biotechnology products showing longer-term promise for adaptation to climate change

Product	Trait	Function	Reference
Drought-tolerant rice	HARDY (HRD) gene from *Arabidopsis*, reducing transpiration and enhancing photosynthetic assimilation	Reduced transpiration, increasing biomass/water use ratio, adaptive increase of root mass under water stress	Karaba et al. (2007)
Drought-tolerant tobacco (model)	Delayed drought-induced leaf senescence	Retained water content and photosynthesis resulting in minimal yield loss under drought (30 % normal water requirements)	Rivero et al. (2007)
Drought-tolerant maize	Expression of glutamate dehydrogenase (gdhA) gene from *E. coli*	Germination and grain biomass production under drought increased	Castiglioni et al. (2008)
Drought-tolerant maize	Enhanced expression of phosphatidylinositol-specific phospholipase by ZmNF-YB2 reducing stomatal conductance and so leaf temperature and water loss	Grain yield increases through reduced wilting and maintenance of photosynthesis under drought	Nelson et al. (2007)
Salt-tolerant rice	A QTL (Saltol) associated with drought resistance	Allows close to normal yield under high salinity situations (Bangla Desh)	IRRI News (2009)

- Development of crop varieties tolerant to biotic and abiotic stresses, drought, salinity and high temperature, flood and submergence, etc., through marker-assisted selection process
- Transgenic approaches to retard senescence in fruits to reduce postharvest losses
- Development of livestock and fish varieties to cope with biotic and abiotic stress levels
- Development of crops with enhanced water and nitrogen use efficiency and CO_2 fixation potential to increase productivity and for reducing emissions of greenhouse gases
- Building of soil carbon banks through fertilizer trees for enhancing soil nutrient status
- Screening of indigenous plant and animal gene pools and cataloguing them according to specific traits of agronomic value and conservation and establishment of gene banks in situ and ex situ
- Strengthening basic research in plant sciences including phenomics and linking basic research to farm level
- Developing and spreading true potato seed (TPS) methodology for potato
- Development of hybrid rice strains characterized by hybrid vigor in the development of root system
- Breeding salinity-tolerant crop varieties for cultivation in coastal areas, based on genetic engineering techniques

12.1.7.2 Technologies and Practices

- Use of micro-propagation and tissue-culture techniques for rapid bulking of improved varieties
- Formulation of a dynamic contingent seed production and distribution plan
- Application of modern biotechnology tools such as genetic transformation, marker-assisted selection, doubled haploid, and mutation breeding to supplement traditional breeding methods
- In vitro conservation of critical adaptive genes and genetic traits
- Shifting the breeding strategy to per day rather than per crop productivity for wheat
- Promotion of sea-water farming through agri–aqua farms and below sea-level farming as in vogue in some parts of Kerala

12.1.8 Conclusions

Genetic resources for food and agriculture safeguard agricultural production and provide options for coping with climate change (e.g., seeds with higher yields, better quality, earlier maturity, better adaptation, and higher resistance to diseases, insects, and environmental stress). Domesticated species, breeds, and varieties and their wild relatives will be the main source of genetic resources for adaptation to climate change. In situ and ex situ conservation and sustainable use of genetic resources for food and agriculture and their wild relatives will be critical for the development of climate-resilient agriculture. With the interdependence of countries increasing, the transfer of genetic resources and the knowledge related to their use needs to be supported through effective cooperation between countries. The fair and equitable sharing of benefits arising from the use of genetic resources also needs to be properly addressed.

12.2 Crop Production Adaptation

12.2.1 Key Issues

- Improved agronomic practices to reduce farm losses
- Conservation and precision farming
- Knowledge management
- Soil conservation, bio-fertilizer
- Policy instruments for optimum land use

The most effective way to address climate change is to adopt a sustainable development pathway by shifting to environmentally sustainable technologies and promotion and accelerated adaptation of energy-efficient equipments (Mathur 2009), renewable energy, and conservation of natural resources. Improved agronomic practices have the potential to help reduce farm level losses through improved soil treatment; increased water-use efficiency; judicious use of chemicals, labor, and energy; and increased soil carbon storage. Targeted resource-conserving technologies offer new opportunities for better livelihoods for the resource poor, small, and marginal farmers.

To cope with the challenges of climate change, crop production must adapt (e.g., crop varietal selection, plant breeding, cropping patterns, and ecosystem management approaches) and become resilient to changes (frequency and intensity). Adapting cropping practices and approaches will be related to local farmers' knowledge, requirements, and priorities. Sustainable crop production provides farmers with options for farming sustainably, taking into account the local ecosystem. Most adaptation options build on existing practices and sustainable agriculture rather than new technologies. Changes to water and soil management will be central to adaptation for most farming systems. Pest and disease management will also be critical.

Improving adaptation of the agricultural sector to the adverse effects of climate change will be imperative for protecting and improving the livelihoods of the poor and ensuring food security (FAO 2012). Environmental stresses have always had an impact on crop production, and farmers have always looked for ways to manage these stresses. In practical terms, climate change adaptation requires more than simply maintaining the current levels of performance of the agricultural sector; it requires developing a set of robust and yet flexible responses that will improve the sector's performance even under the changing conditions brought about by climate change engenders. Some ways of local adaptation to stress is through plant breeding, pest management strategies, and seed delivery systems, to name a few.

Indeed, by improving the efficiency of agricultural production, emissions can be reduced and sequestration capacity enhanced. Conversely, climate change will have a significant impact on crop production, but alternative adaptation approaches and practices can address this by helping to reduce the net GHG emissions while maintaining or improving yields (FAO 2011; Pretty et al. 2011).

Examples of changes in climatic conditions that influence crop systems include rain quantity and distribution, and consequently water availability; extreme events, such as floods and droughts; higher temperatures; and shifting seasons. The rate of climate change may exceed the rate of adaptation for natural systems, including crops, and this creates high concern for food availability (Allara et al. 2012). In essence, what this means is that crops that were usually planted in one area may no longer be able to grow there. In addition, the ecosystem services that ensure crop growth (e.g., pollination, soil biodiversity) may also be affected. For these reasons, it is necessary to address crop production at the farming systems level. With appropriate technical, institutional, socioeconomic, and policy infrastructure in place, there is a huge potential for crop management practices and approaches to adapt to, and contribute to, the mitigation of climate change.

Different approaches and practices for sustainable crop production can contribute to climate change adaptation. They provide options for location-specific contexts and should be adapted with local farmers/farming communities (FAO-PAR 2011; FAO 2012). Examples include:

- Ecosystem-based approaches
- Conservation agriculture
- Integrated nutrient and soil management
- Mulch cropping
- Cover cropping
- Alterations in cropping patterns and rotations
- Crop diversification
- Ecological pest management
- Grassland management
- Water and irrigation management
- Landscape-level pollination management
- Organic agriculture

12.2.2 Cultural Practices

Simple, affordable, and accessible technologies like mulching and use of shelters and raised beds help to conserve soil moisture, prevent soil degradation, and protect crops from heavy rains, high temperatures, and flooding. The use of organic and inorganic mulches is common in high-value crop production systems. These protective coverings help reduce evaporation, moderate soil temperature, reduce soil runoff and erosion, protect grains/fruits from direct contact with soil, and minimize weed growth. In addition, the use of organic materials as mulch can help enhance soil fertility, structure, and other soil properties. Rice straw is abundant in rice-growing areas and generally recommended for summer crop production. Polythene, *Saccharum* spp., and *Canna* spp. can also be used as mulching materials. In the areas where temperatures are high, dark-colored plastic mulch is recommended in combination with rice straw (AVRDC 1990). Dark color of plastic mulch prevents sunlight from reaching the soil surface, and the rice straw insulates the plastic from direct sunlight, thereby preventing the soil temperature rising too high during the day.

During the hot rainy season, vegetables such as tomatoes suffer from yield losses caused by heavy rains. Simple, clear plastic rain shelters prevent water logging and rain impact damage on developing fruits, with consequent improvement in tomato yields (Midmore et al. 1992). Fruit cracking and the number of unmarketable fruits are also reduced. Another form of shelter using shade cloth can be used to reduce temperature stress. Planting vegetables in raised beds can ameliorate the effects of flooding during the rainy season (AVRDC 1981).

12.2.3 Land Management Practices

Changing land management practices such as shifting production away from marginal areas and altering the intensity of fertilizer and pesticide application as well as capital and labor inputs can help reduce risks from climate change in farm production. Adjusting the cropping sequence, including changing the timing of sowing, planting, spraying, and harvesting, to take advantage of the changing duration of growing seasons and associated heat and moisture levels, is another option. Altering the time at which fields are sowed or planted can also help farmers regulate the length of the growing season to better suit the changed environment. Farmer adaptation can also involve changing the timing of irrigation or use of other inputs such as fertilizers.

12.2.4 Conservation Tillage

Tillage is the agricultural preparation of the soil by mechanical, draught-animal, or human-powered agitation, such as plowing, digging, overturning, shoveling, hoeing, and raking. Small-scale farming tends to use smaller-scale methods using hand tools and in some cases draught animals, whereas medium to large-scale farming tends to use the larger-scale methods such as tractors (Fig. 12.3). The overall goal of tillage is to increase crop production while conserving resources (soil and water) and protecting the environment.

Conservation tillage refers to a number of strategies and techniques for establishing crops in a previous crop's residues, which are purposely

Fig. 12.3 Conservation tillage using disks and tines (Source: Peeters Agricultural Machinery, Netherlands)

Fig. 12.4 Happy seeder for sowing in presence of residues (Photo courtesy: CSISA (CIMMYT-IRRI), New Delhi)

left on the soil surface. Conservation tillage practices typically leave about one-third of crop residue on the soil surface. This slows water movement, which reduces the amount of soil erosion. Conservation tillage is suitable for a range of crops including grains, vegetables, root crops, sugarcane, cassava, fruit, and vines.

Conservation tillage is a popular technology in the Americas, with approximately 44 % practiced in Latin America. Studies suggest that there is great potential to bring this technology to Africa, Asia, and Eastern Europe, although limiting factors have to be taken into account (Derpsch 2001). The most common conservation tillage practices are no-till, ridge-till, and mulch-till.

No-till is a way of growing crops without disturbing the soil. This practice involves leaving the residue from last year's crop undisturbed and planting directly into the residue on the seedbed. No-till requires specialized seeding equipment designed to plant seeds into undisturbed crop residues and soil (Fig. 12.4). No-till farming changes weed composition drastically. Faster growing weeds may no longer be a problem in the face of increased competition, but shrubs and trees may begin to grow eventually. Cover crops – "green manure" – can be used in a no-till system to help control weeds. Leguminous cover crops which are typically high in nitrogen can often increase soil fertility.

In ridge-till practices, the soil is left undisturbed from harvest to planting and crops are planted on raised ridges (Fig. 12.5). Planting usually involves the removal of the top of the ridge. Planting is completed with sweeps, disk openers, coulters, or row cleaners. Residue is left on the surface between ridges. Weed control is accomplished with cover crops, herbicides, and/or cultivation. Ridges are rebuilt during row cultivation.

Mulch-till techniques involve disturbing the soil between harvesting one crop and planting the next but leaving around a third of the soil covered with residues after seeding. Implements used for mulch-till techniques include chisels, sweeps, and field cultivators.

Unpredictability of rainfall and an increase in the mean temperature may affect soil moisture levels leading to damages to and failures in crop yields. Conservation tillage practices reduce risk from drought by reducing soil erosion, enhancing moisture retention, and minimizing soil impaction. In combination, these factors improve resilience to climatic effects of drought and floods. Improved soil nutrient recycling may also help combat crop pests and diseases.

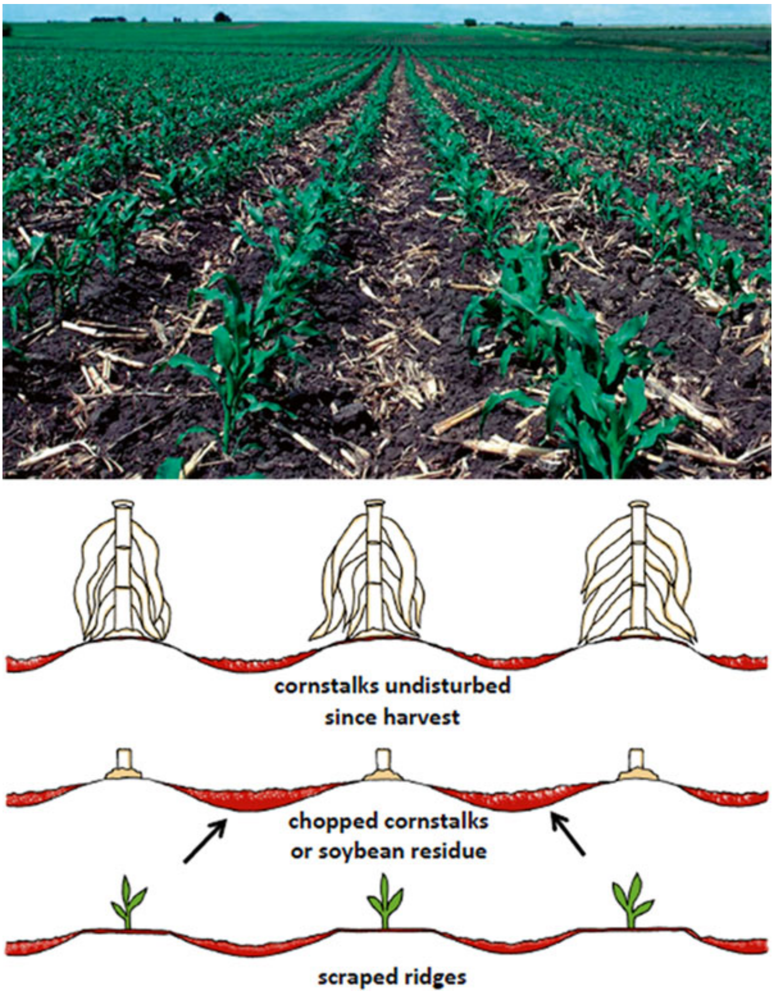

Fig. 12.5 Ridge tillage (Source: Adapted from Introduction to Ridge-Tillage for Corn and Soybeans. Purdue University Cooperation Extension Service ID-180)

12.2.4.1 Advantages

Conservation tillage benefits farming by minimizing erosion, increasing soil fertility, and improving yield. Plowing loosens and aerates the soil which can facilitate some deeper penetration of roots. Tillage is believed to help in the growth of microorganisms present in the soil and helps in the mix of the residue from the harvest, organic matter, and nutrients evenly in the soil. Conservation tillage systems also benefit farmers by reducing fuel consumption and soil compaction. By reducing the number of times the farmer travels over the field, farmers make significant savings in fuel and labor. Labor inputs for land preparation and weeding are also reduced once the system becomes established. In turn, this can increase time available for additional farm work or off-farm activities for livelihood diversification. Also once the system is established, requirement for herbicides and fertilizers can be reduced. The total economic benefits arising from adoption of the no-tillage technique in small farms of generally less than 20 ha in Paraguay have reached around $941 million.

12.2.4.2 Disadvantages

Conservation tillage may require the application of herbicides in the case of heavy weed infestation, particularly in the transition phase, until the new balance of weed populations is established. The practice of conservation may also lead to soil compaction over time; however, this can be prevented with chisel ploughs or sub-soilers. Initial investment of time and money along with purchases of equipment and herbicides will be necessary for establishing the system. Higher levels of surface residue may result in higher plant disease and pest infestations, if not managed properly. There is a strong relationship between this technology and appropriate soil characteristics. This is detrimental in high clay content and compact soils.

12.2.5 Adjusting Cropping Season

Adjustment of planting dates to minimize the effect of temperature increase-induced spikelet sterility can be used to reduce yield instability, by avoiding having the flowering period to coincide with the hottest period. Adaptation measures to reduce the negative effects of increased climatic variability as normally experienced in arid and semiarid tropics may include changing of the cropping calendar to take advantage of the wet period and to avoid extreme weather events (e.g., typhoons and storms) during the growing season. Cropping systems may have to be changed to include growing of suitable cultivars (to counteract compression of crop development), increasing crop intensities (i.e., the number of successive crop produced per unit area per year), or planting different types of crops. Farmers will have to adapt to changing hydrological regimes by changing crops.

12.2.6 Efficient Use of Resources

The resource-conserving technologies (RCTs) encompass practices that enhance resource- or input-use efficiency and provide immediate, identifiable, and demonstrable economic benefits such as reduction in production costs; savings in water, fuel, and labor requirements; and timely establishment of crops, resulting in improved yields. Yields of wheat in heat- and water-stressed environments can be raised significantly by adopting RCTs, which minimize unfavorable environmental impacts, especially in small- and medium-scale farms. Resource-conserving practices like zero-tillage (ZT) can allow farmers to sow wheat sooner after rice harvest, so the crop heads and fills the grain before the onset of pre-monsoon hot weather. As the average temperatures in the region rise, early sowing will become even more important for wheat. Field results have shown that the RCTs are increasingly being adopted by farmers in the rice–wheat belt of the Indo-Gangetic Plains because of several advantages of labor saving, water saving, and early planting of wheat. These approaches of crop management should be coupled with the measures of crop improvement for wider adaptation to climate change. Soil and water management is highly critical for adaptation to climate change. With higher temperatures and changing precipitation patterns, water will further become a scarce resource. Serious attempts towards water conservation, water harvesting improvement in irrigation accessibility, and water-use efficiency will become essential for crop production and livelihood management. Farmers have to be trained and motivated for adopting on-farm water conservation techniques, micro-irrigation systems for better water-use efficiency, selection of appropriate crops, etc. Principles of increasing water infiltration include improvement in soil aggregation; decreasing runoff with use of contours, ridges, vegetative hedges, etc.; and reducing soil evaporation with use of crop residues mulch for better management of soil water.

12.2.7 Crop Diversification

Crop diversification, which can be defined as increasing the number of crops or the varieties and hybrids of a particular crop, is a potential farm-level response to climatic variability and change (Bradshaw et al. 2005). Crop diversification in a subsistence farming system provides an alternative means of income generation for smallholder farmers, the majority of whom are vulnerable to climate change. Because of changing rainfall patterns and water resource depletion, the existing cropping pattern is becoming less productive. Thus, crop intensification, through mixed cropping and integration of high-value crops such as horticultural production, is gaining prominence as a climate change adaptation strategy. Riyannsh (2008) noted that "due to shrinking natural resources and ever-increasing demand for food and raw materials, agricultural intensification is the main course of future growth of agriculture." Bindhumadhavan (2005) stated that it is time to critically redesign alternative cropping patterns based on agroclimatic zones and to demonstrate them in farmers' fields. Hence the need for crop diversification from:

- Low-value to high-value crops (resulting in a price-risk benefit)
- Low-yielding to high-yielding crops (resulting in a yield-risk benefit)
- High water-use crops to water-saving crops
- Single cropping to multiple or mixed cropping
- Subsistence food crop to market-oriented crop
- Raw material production to processing and value addition

Diversification of crop varieties, including replacement of plant types, cultivars, and hybrids, with new varieties intended for higher drought or heat tolerance, is being advocated as having the potential to increase productivity in the face of temperature and moisture stresses. Diversity in the seed genetic structure and composition has been recognized as an effective defense against disease and pest outbreak and climatic hazards. Moreover, demand for high-value food commodities, such as fruits and vegetables, is increasing because of growing income and urbanization. This is reducing the demand for traditional rice and wheat. Diversification from rice–wheat towards high-value commodities will increase income and result in reduced water and fertilizer use. However, there is a need to quantify the impacts of crop diversification on income, employment, soil health, water use, and greenhouse gas emissions. A significant limitation of diversification is that it is costly in terms of the income opportunities that farmers forego, i.e., switching of crop can be expensive, making crop diversification typically less profitable than specialization. Moreover, traditions can often be difficult to overcome and will dictate local practices.

Shift to growing cash crops with existing irrigation technologies which will earn more income and enable farmer to invest in upgrading irrigation systems among other AWM interventions. Crop diversification also includes integration of different varieties of crops, both food and cash crops. In the African context, six crops seem to have large-scale potential: sugarcane, sweet sorghum, maize and cassava for ethanol, and oil palm and jatropha for biodiesel (Sielhorst et al. 2008).

At the individual farm scale, the simplest measure of crop diversity is the total number of different crops per farm. Crop diversification acts to reduce susceptibility to climatic variability such as floods or droughts that might result in crop failure. At the same time, it increases the number of marketable activities such as adding livestock to a cash crop operation or undertaking value-added processing and hence serves to reduce farmers' risks resulting from weather fluctuations. Additionally, other risk-reducing strategies, such as crop insurance or the securing of off-farm income, may be complimentary.

Increasing diversity of production at farm and landscape level is an important way to improve the resilience of agricultural systems (FAO and OECD 2012; HLPE 2012). Diversifying production can also improve efficiency in the use of land, as is the case in agro-forestry systems, for instance, and of nutrients with the introduction of legumes in the rotation or in integrated crop/livestock or rice/aquaculture systems. Studies show that they can also be more efficient in terms of income. Farms that both grow crops and exploit forest generate a higher and more stable income. Regions growing more diverse varieties of barley have a higher average yield than areas growing a single variety. More diversified systems can also spur the development of local markets.

12.2.8 Relocation of Crops in Alternative Areas

Climate change in terms of increased temperature, CO_2 level, droughts, and floods would affect production of crops. But, the impact will be different across crops and regions. There is a need to identify the crops and regions that are more sensitive to climate changes/variability and relocate them in more suitable areas. For example, it is apprehended that increased temperature would affect the quality of crops, particularly important aromatic crops such as basmati rice and tea. Alternative areas that would become suitable for such crops from quality point of view need to be identified and assessed for their suitability.

12.2.9 Integrated Nutrient Management (INM)

Soil is a fundamental requirement for crop production as it provides plants with anchorage, water, and nutrients. A certain supply of mineral and organic nutrient sources is present in soils, but these often have to be supplemented with external applications, or fertilizers, for better plant growth. Fertilizers enhance soil fertility and are applied to promote plant growth, improve crop yields, and support agricultural intensification.

Fertilizers are typically classified as organic or mineral. Organic fertilizers are derived from substances of plant or animal origin, such as manure, compost, seaweed, and cereal straw. Organic fertilizers generally contain lower levels of plant nutrients as they are combined with organic matter that improves the soils' physical and biological characteristics. The most widely used mineral fertilizers are based on nitrogen, potassium, and phosphate.

Optimal and balanced use of nutrient inputs from mineral fertilizers will be of fundamental importance to meet growing global demand for food. Mineral fertilizer use has increased almost fivefold since 1960 and has significantly supported global population growth. It is estimated that nitrogen-based fertilizer has contributed 40 % to the increases in per capita food production in the past 50 years. Nevertheless, environmental concerns and economic constraints mean that crop nutrient requirements should not be met solely through mineral fertilizers. Efficient use of all nutrient sources, including organic sources, recyclable wastes, mineral fertilizers, and biofertilizers, should therefore be promoted through INM.

The aim of INM is to integrate the use of natural and man-made soil nutrients to increase crop productivity and preserve soil productivity for future generations. Rather than focusing nutrition management practices on one crop, INM aims at optimal use of nutrient sources on a cropping system or crop rotation basis. This encourages farmers to focus on long-term planning and make greater consideration for environmental impacts.

INM relies on a number of factors, including appropriate nutrient application and conservation and the transfer of knowledge about INM practices to farmers and researchers. Boosting plant nutrients can be achieved by a range of practices such as terracing, alley cropping, conservation tillage, intercropping, and crop rotation. This section will focus on INM as it relates to appropriate fertilizer use. In addition to the standard selection and application of fertilizers, INM practices include new techniques such as deep placement of fertilizers and the use of inhibitors or urea coatings (use of urea coating agent helps to retort the activity and growth of the bacteria responsible for denitrification) that have been developed to improve nutrient uptake.

Key components of the INM approach include:

- Testing procedures to determine nutrient availability and deficiencies in plants and soils. These are:
  - Plant symptom analysis – visual clues can provide indications of specific nutrient deficiencies. For example, nitrogen-deficient plants appear stunted and pale compared to healthy plants.
  - Tissue analysis and soil testing – where symptoms are not visible, postharvest tissue and soil samples can be analyzed in a laboratory and compared with a reference sample from a healthy plant.
- Systematic appraisal of constraints and opportunities in the current soil fertility management practices and how these relate to the nutrient diagnosis, for example, insufficient or excessive use of fertilizers.

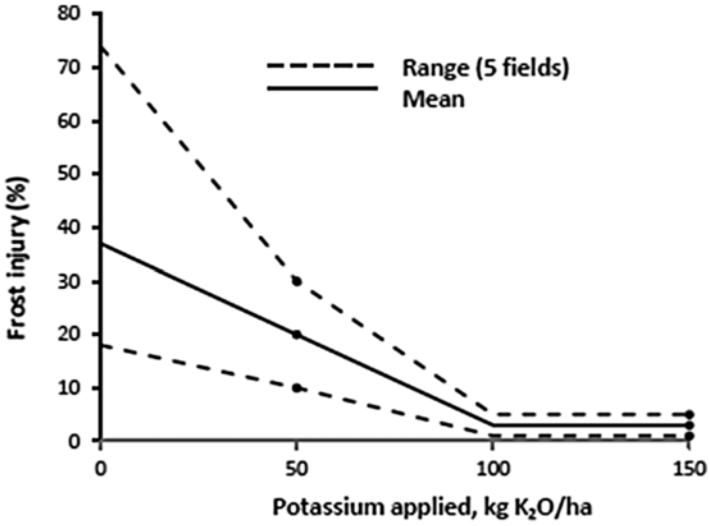

Fig. 12.6 Effect of potassium application on frost injury to potato crop

- Assessment of productivity and sustainability of farming systems. Different climates, soil types, crops, farming practices, and technologies dictate the correct balance of nutrients necessary. Once these factors are understood, appropriate INM technologies can be selected.
- Participatory farmer-led INM technology experimentation and development. The need for locally appropriate technologies means that farmer involvement in the testing and analysis of any INM technology is essential.

Harsh climatic conditions are a major cause of soil erosion and the depletion of nutrient stocks. By increasing soil fertility and improving plant health, INM can have positive effects on crops in the following ways:

- A good supply of phosphorous, nitrogen, and potassium has been shown to exert a considerable influence on the susceptibility or resistance of plants towards many types of pests and diseases.
- A crop receiving balanced nutrition is able to explore a larger volume of soil in order to access water and nutrients. In addition, improved root development enables the plant to access water from deeper soil layers. With a well-developed root system, crops are less susceptible to drought.
- Under increasingly saline conditions, plants can be supplemented with potassium to maintain normal growth.
- With appropriate potassium fertilization, the freezing point of the cell sap is lowered, thus improving tolerance to colder conditions (Fig. 12.6).

12.2.9.1 Advantages

INM enables the adaptation of plant nutrition and soil fertility management in farming systems to site characteristics, taking advantage of the combined and harmonious use of organic and inorganic nutrient resources to serve the concurrent needs of food production and economic, environmental, and social viability. INM empowers farmers by increasing their technical expertise and decision-making capacity. It also promotes changes in land use, crop rotations, and interactions between forestry, livestock, and cropping systems as part of agricultural intensification and diversification.

12.2.9.2 Disadvantages

Besides facilitating adaptation to climate change in the agriculture sector, the INM approach is also sensitive to changes in climatic conditions and could produce negative effects if soil and crop nutrients are not monitored systematically and changes to fertilizer practices made accordingly. In Africa, high transport costs in land-locked countries contribute to prohibitively high fertilizer prices (FAO 2008). In the case of small-scale farmers, these costs may represent too high a proportion of the total variable cost of production, thus ruling out inorganic fertilizer as a feasible option.

12.2.10 Biological Nitrogen Fixation

In agricultural systems, some types of microbes can carry out biological nitrogen fixation (BNF) as free-living organisms: heterotrophic and autotrophic bacteria and cyanobacteria. Other microorganisms can only fix nitrogen through a symbiotic relationship with plants, mainly legume species. In agricultural areas, about 80 % of BNF is achieved by the symbiotic association between legumes and the nodule bacteria, rhizobia. Farmers have some scope to influence BNF, through legume selection, the proportion of legume and grass seed in forage mixtures, inoculation with bacteria such as rhizobia, crop nutrition (especially nitrogen and phosphorous), weed, disease and pest controls, planting time, cropping sequence and intensity, and defoliation frequency of forage swards. In perennial temperate forage legumes, red clover and lucerne can typically fix 200–400 kg of nitrogen per hectare (whole plant fixation, above- and belowground) (FAO 2009).

12.2.11 Harnessing Indigenous Technical Knowledge of Farmers

Farmers in South Asia, often poor and marginal, are experimenting with the climatic variability for centuries. There is a wealth of knowledge on the range of measures that can help in developing technologies to overcome climate vulnerabilities. There is a need to harness that knowledge and fine-tune them to suit the modern needs. Traditional ecological knowledge of people developed and carried which have stood the test of time could provide insights and viable options for adaptive measures. Anthropological and sociological studies have highlighted the importance of community-based resource management and social learning to enhance their capacity to adapt to the impacts of future climate change. Tribal and hill knowledge systems are pregnant with potential indigenous practices used for absorption and conservation of rainwater, nutrient and weed management, crop production, and plant protection. Their belief systems have effectively helped in weather forecasting and risk adjustment in crop cultivation. During the course of their habitation, the indigenous people of Himalayan terrain region through experience, experimentation, and accumulated knowledge have devised ways of reducing their vulnerability to natural hazards. Studies have shown that their understanding was fairly evolved in the matters of earthquake, landslide, and drought and they have devised efficient ways of mitigating the effect of natural or climatic changes.

12.2.12 Interventions

12.2.12.1 Research and Development

- Promotion of organic agriculture research.
- Develop technologies for improvement of water-use efficiency.
- Develop technologies for management of salt-affected soils and waterlogged areas.
- Explore potential of change in sowing time as adaptation strategy.

12.2.12.2 Technologies and Practices

- Promoting agriculture heritage and traditional methods for conservation and management of resources
- Soil enrichment through intercrop transfers (use of legumes), promotion of conservation agriculture practices to enhance soil organic carbon, water conservation, and minimize soil erosion
- Developing and applying resource conservation technologies (RCTs) like zero-tillage, raised bed planting, laser land leveling, etc., for enhancing soil productivities
- Promoting inter-terrace land treatment, emphasis on soil quality, organic farming,

promotion of integrated farming systems, and other measures that encourage resource conservation
- Introducing improved farm machinery for enabling crops to be grown with minimal tillage (reduced tillage) or without tillage (no tillage) resulting in soil carbon gains
- Encouraging protected cultivation in areas which face extreme weather conditions
- Low-cost greenhouses, along with micro-irrigation and fertigation techniques
- Promoting new technologies such as SRI (System of Rice Intensification)
- Development of contingency plans for farming practices to cope with sudden climatic variability
- Introduction of post flood agriculture rehabilitation measures such as crops like yellow-flesh-sweet potato, sunflower, fodder, sathi maize, etc.
- Developing mangrove and non-mangrove bioshields to minimize the impact of coastal storms and sea-water inundation

12.3 Water Adaptation

12.3.1 Key Issues

- Promoting water-use efficiency in irrigation
- Research and development in the areas of energy-efficient water systems
- Developing mechanisms for integrated management of rainwater, surface, and groundwater
- Policy instruments for PPP
- Strengthen local institutions in managing water allocation and utilization

Two-thirds of the cultivated land is rainfed and suffers from water scarcity. Effective management of available water, increasing water-use efficiency, and establishment of additional sustainable sources of water emerge as the primary issues that need to be addressed. Strategies under this dimension would focus on the application of a range of technologies coupled with demand and supply-side management solutions to enhance water-use efficiency for irrigation. While some technologies are available for direct application and can be implemented in the short term, there are other emerging areas like recharging of aquifers, conjunctive use of surface and groundwater, controlled extractions, etc., that would require collaboration and capacity building for technology absorption before being put into sustainable use.

According to the IPCC, by 2020 rainfed crop yields in some countries will decrease by half. The impact of climate change on farmers and their livelihoods could be catastrophic. Several practical options for adaptation for livelihood systems to changing climatic conditions exist. All efforts should therefore be made to refine, augment, and deploy them appropriately and urgently. The slogan “more crop per drop” is becoming more appropriate as countries strive to contend with decreasing water resources. Existing agricultural water management (AWM) technologies, such as drip irrigation and rainwater harvesting, have the potential to double, even quadruple, rainfed crop yields in many parts of the world.

It is commonly acknowledged that most of the impacts from climate change will relate to water (UN-Water 2010). How water is managed will be at the center of climate change adaptation strategies. This is particularly true in rural areas and in the agriculture sector, where water plays a critical role in crop and animal production (including fish), and the management of ecosystems, including forests, rangeland, and cropland.

The most immediate impact of climate change on water for agriculture will be through the increased variability of rainfall, higher temperatures, and associated extreme weather events, such as droughts and floods. In the medium to long term, climate change will affect water resources and reduce the availability or reliability of water supplies in many places already subject to water scarcity.

Water management and the efficient use of available water will be of fundamental importance in building resilient production systems and improving the management of climate change-induced risks. The efficient and equitable management of water catchments is generally only possible when done in a landscape context and combined with farm-level water management practices. Water management requires common agreements on the modalities of use. These agreements will be best achieved through participatory governance processes related to integrated land-use planning. Large catchments, such as river basins, need layers of nested planning approaches, starting at the river basin scale, with implementation activities planned in detail on the landscape scale.

Water resources management strategy is thus the key to ensuring that agricultural production can withstand the stresses caused by climate change. Improved AWM is one of the "best bets" for adapting agricultural production to climate change and variability. However, accomplishing this "Blue Revolution" is a significant challenge. The current poor performance in terms of water-use efficiency, plus competition over diminishing water resources, suggests the need for investment in better water management systems. Also, where access to irrigation is limited, farmers need to develop water conservation and rainwater harvesting systems to maximize on-farm water management.

Rainwater harvesting complements irrigation and enhances farmers' profitability. Rainwater harvesting for supplemental irrigation, for example, yielded net profits of US$ 150–600 per ha in Burkina Faso and US$ 110–500 in Kenya. Water management is also improved by having a greater diversity of options for water sources, such as small streams, shallow wells, bore wells, and rainwater storage. Other irrigation options include surface irrigation methods (furrows and small basins), pressurized systems (sprinkler and both high- and low-head drip), and water lifting technologies (gravity, manual, and pumps – motorized, wind-driven, and solar).

Another management strategy is the upgrading of rainfed agriculture through integrated rainwater harvesting systems and complementary technologies such as low-cost pumps and water application methods, such as low-head drip irrigation kits. Rainwater harvesting systems include two broad categories:

- In situ soil moisture conservation – technologies that increase rainwater infiltration and storage in the soil for crop use
- Runoff storage for supplemental irrigation using storage structures such as farm ponds, earth dams, water pans, and underground tanks

Increasing investment in AWM is one of the promising climate change adaptation strategies for farmers. AWM can contribute to agricultural growth and reduce poverty, since better management of water will translate into intensification and diversification in developed land, expansion of irrigated areas, increases in food and feed production, and environmental conservation.

Maintaining a stable water supply for agriculture requires both demand-side strategies, such as recycling and conserving water, and supply-side strategies, such as water storage (Thornton and Cramer 2012).

The identified and recommended feasible AWM interventions should be promoted by development agencies to enhance farmers' strategies for coping with climate change and variability. The following are some of the promising AWM interventions that should be considered:

- Irrigation development includes rehabilitation of existing schemes to improve water-use efficiency and productivity. This covers both gravity-fed (most preferable, where applicable, due to low operation and maintenance cost) and pumped schemes (from either groundwater or surface water sources – rivers, dams, etc.).
- Upgrading rainfed agriculture through in situ rainwater harvesting systems – farming practices that retain water in crop land (terraces, contour bunds, ridges, tied ridges, planting pits, conservation agriculture, etc.).
- Supplementary irrigation systems (farming practices that supply water to crops during critical growth stages) are appropriate where irrigation water is inadequate for full irrigation or where crops are grown under rainfed conditions and only irrigated during intra-seasonal dry spells or in case of early rainfall cessation.
- On- or off-farm water storage systems – rainwater harvesting and management systems allow the farmers to store runoff in ponds (unlined or lined). For communal land or farmers with appropriate sites, large storage

structures such as earth dams or water pans can be considered. Water can be supplied to crop land either by gravity or pumping and applied to crops either by surface irrigation (furrow or basin) or pressurized irrigation (especially low-head irrigation systems). Other rainwater harvesting structures such as sand dams, subsurface dams, and rock catchment systems fall under this category.

- Spate irrigation – flood diversion and spreading into crop land is appropriate in areas where flash floods occur, especially in lowlands adjacent to degraded or rocky catchments.
- Micro-irrigation systems – these include various technologies, among which low-head drip irrigation kits are the most appropriate. Low-head drip kits can use many different water sources. They are mainly used for irrigating high-value crops like garden vegetables and orchard fruits and for green maize production at times.
- Land drainage, wetland management, and flood recession are appropriate for areas with excess soil moisture and should therefore be considered where necessary.
- On the demand side, water-use efficiency, through, for example, recycling of water, is the main adaptation intervention. Greater use of economic incentives, including metering and pricing, can encourage water conservation and the reallocation of water to highly valued uses (IWMI 2007).
- On the supply side, more strategic water storage is a key intervention for the adaptation of agriculture to climate change. Water storage provides a buffer and can offset the risks associated with floods or droughts. Water storage options include reservoirs, ponds, tanks, aquifers, soil moisture, and natural wetlands (McCartney and Smakhtin 2010).
- The rate of glacier deposition and melting under climate change will be a major determinant of water availability for agriculture, but remains highly uncertain and under-studied. In China, for example, the best current knowledge is that runoff from glaciers may peak from 2030 to 2050, followed by a gradual decline (Piao et al. 2010).
- Irrigation will be an important adaptation option in some regions. It compensates both for long-term declines in water supply and for short-term deficits associated with increasing climate variability. This will be the key for Brazil, for example (Rosenzweig et al. 2004; Cunha et al. 2012).
- Irrigation will not work as an adaptation option everywhere. In sub-Saharan Africa, water supply reliability (ratio of water consumption to requirements) is expected to worsen and will limit the adaptation potential of irrigation. Even farming regions that are expected to have sufficient water under climate change, such as the Danube basin of Europe, may not be able to expand irrigation for adaptation strategy, as models suggest that this would increase water supply unreliability (Rosenzweig et al. 2004).
- Climate change mitigation measures, such as reforestation, can assist adaptation by increasing the capacity of soils and landscapes to hold water (Thornton and Cramer 2012).

There are several methods of applying irrigation water and the choice depends on the crop, water supply, soil characteristics, and topography. Surface irrigation methods are utilized in more than 80 % of the world's irrigated lands, yet its field-level application efficiency is often 40–50 %. To generate income and alleviate poverty of the small farmers, promotion of affordable, small-scale drip irrigation technologies are essential. Drip irrigation minimizes water losses due to runoff, and deep percolation and water savings of 50–80 % are achieved when compared to most traditional surface irrigation methods. Crop production per unit of water consumed by plant evapotranspiration is typically increased by 10–50 %. Thus, more plants can be irrigated per unit of water by drip irrigation and with less labor. The water-use efficiency by chili pepper was significantly higher in drip irrigation compared to furrow irrigation, with higher efficiencies observed with high delivery rate drip irrigation regimes (AVRDC 2005). For drought-tolerant crops like watermelon, yield differences between furrow and drip irrigated crops were not significantly different; however, the incidence of

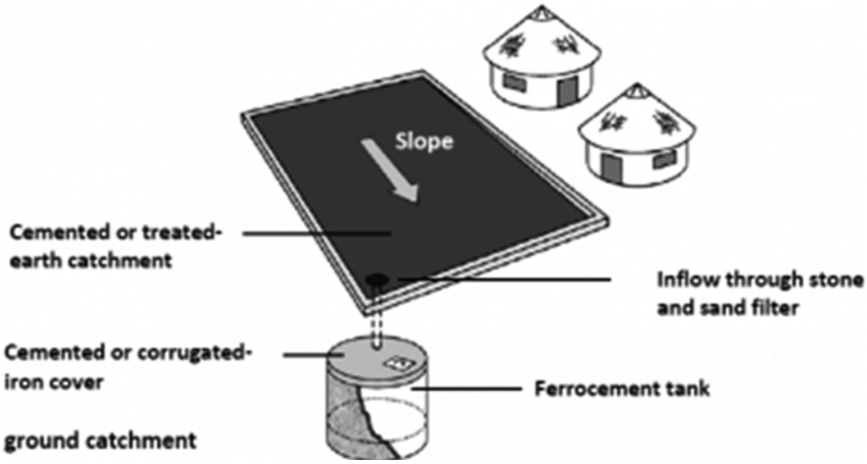

Fig. 12.7 Ground catchment system

Fusarium wilt was reduced when a lower drip irrigation rate was used. In general, the use of low-cost drip irrigation is cost-effective, labor-saving, and allows more plants to be grown per unit of water, thereby both saving water and increasing farmers' incomes at the same time. Prominent (adaptation) technologies in this area are:

- Rainwater harvesting
- Sprinkler irrigation
- Drip irrigation
- Fog harvesting

12.3.2 Rainwater Harvesting

Rainfall can provide some of the cleanest naturally occurring water that is available. There is considerable scope for the collection of rainwater when it falls, before huge losses occur due to evaporation, transpiration, and runoff and drainage – before it becomes contaminated by natural means or man-made activities. Rainwater harvesting is a particularly suitable technology for areas where there is no surface water, or where groundwater is deep or inaccessible due to hard ground conditions, or where it is too salty or acidic.

Rainwater harvesting is defined as a method for inducing, collecting, storing, and conserving local surface runoff (rain or surface water flow that occurs when soil is infiltrated to full capacity) for agriculture in arid and semiarid regions (Boers and Ben-Asher 1982). Both small- and large-scale structures are used for rainwater harvesting collection and storage including water pans, tanks, reservoirs, and dams. The catchment area is the area where the rainfall or water runoff is initially captured and is in most cases either the ground surface or rock surface.

12.3.2.1 Ground-Surface

In the ground surface method, water flowing along the ground during the rains is usually diverted towards a tank below the surface (Fig. 12.7). There is greater possibility of water loss due to infiltration into the ground. The water is generally of lower quality than that collected directly from rainfall. Techniques available for increasing runoff within ground catchment areas include (1) clearing or altering vegetation cover, (2) increasing the land slope with artificial ground cover, and (3) reducing soil permeability by soil compaction and application of chemicals (UNEP 1982). Impermeable membranes can also be used to facilitate runoff. Ground catchment is applicable for low topographic areas and is suitable for large-scale agricultural production as it allows for in situ storage and usage of fresh water for irrigation.

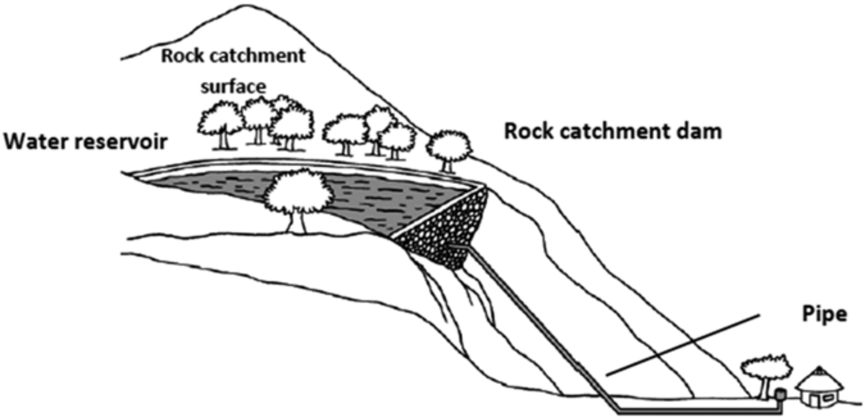

Fig. 12.8 Rock catchment dam

12.3.2.2 Rock Surface

Rock surfaces can also be used as collection catchments. Bedrock surfaces found within rocky top slopes or exposed rock outcrops in lowlands often have natural hollows or valleys which can be turned into water reservoirs by building a dam (Fig. 12.8). Developing a rock catchment area typically involves clearing and cleaning the site from vegetation and marking out the catchment area to be enclosed with gutters. Rock surfaces should not be fractured or cracked, as this may cause the water to leak away to deeper zones or underneath the dam. As with ground catchments, water is generally of lower quality than direct rainfall collection. Water quality can be improved if access to the area (e.g., by animals and children) is limited.

Several types of conveyance systems exist for transporting water from the catchment to the storage device, including gutters, pipes, glides, and surface drains or channels. Larger-scale conveyance systems may require pumps to transfer water over larger distances. These should be constructed from chemically inert materials, such as wood, bamboo, plastic, stainless steel, aluminum, or fiberglass, in order to avoid negatively affecting on water quality (UNEP 1997). In the case of rock catchments, gutters can be constructed from a stone wall built with rough stones/hardcore and joined with mortar.

Storage devices are used to store the water that is collected from the catchment areas and are classified as (1) aboveground storage tanks and (2) cisterns or underground storage vessels. These facilities can vary in size from one cubic meter to up to hundreds of cubic meters for large projects. For storing larger quantities of water, the system will usually require a bigger tank or cistern with sufficient strength and durability. Typically these tanks can be constructed out of bricks coated with cement. For water captured from a rock catchment, a dam is the more common form of storage device.

Climate change is disrupting global rainfall patterns meaning some parts of the world are suffering from a drastic drop in precipitation leading to a fall in water levels in many reservoirs and rivers. In sub-Saharan Africa where two-thirds of the region is desert and dryland, the need for improving water management in the agriculture sector is particularly critical. Rainwater harvesting represents an adaptation strategy for people living with high rainfall variability, both for domestic supply and to enhance crop, livestock, and other forms of agriculture (UNEP and SEI 2009).

Generally, the amount of water made available through rainwater harvesting is limited and should be used prudently to alleviate water stress during critical stages of crop growth. Supplemental irrigation is a key strategy and can help increase yields by more than 100 %. A small investment providing between 50 and 200 mm of extra water per hectare per season for supplemental irrigation, in combination with improved

Fig. 12.9 Farmland sprinkler system in Cajamarca, Peru (Source: Courtesy of David Dennis Rabines Alarcon)

agronomic management, can more than double water productivity and yields in small-scale rainfed agriculture (UNEP and SEI 2009).

12.3.2.3 Advantages

Rainwater harvesting technologies are simple to install and operate. Local people can be easily trained to implement such technologies, and construction materials are usually readily available. Rainwater harvesting is convenient because it provides water at the point of use and farmers have full control of their own systems. Use of rainwater harvesting technology promotes self-sufficiency and has minimal environmental impact. Running costs are reasonably low. Construction, operation, and maintenance are not labor intensive. Water collected is of acceptable quality for agricultural purposes. Other benefits include increasing soil moisture levels and increasing the groundwater table via artificial recharge. Rainwater harvesting and its application to achieving higher crop yields can encourage farmers to diversify their enterprises, such as increasing production, upgrading their choice of crop, purchasing larger livestock animals, or investing in crop improvement inputs such as irrigation infrastructure, fertilizers, and pest management (UNEP and SEI 2009).

12.3.2.4 Disadvantages

The main disadvantage of rainwater harvesting technology is the limited supply and uncertainty of rainfall. Rainwater is not a reliable water source in dry periods or in time of prolonged drought. Low storage capacity will limit rainwater harvesting potential, whereas increasing storage capacity will add to construction and operating costs, making the technology less economically viable. The effectiveness of storage can be limited by the evaporation that occurs between rains. In water basins with limited surplus supplies, rainwater harvesting in the upstream areas may have a damaging impact downstream and can cause serious community conflict. Also, when runoff is generated from a large area and concentrated in small storage structures, there is a potential danger of water quality degradation, through introduction of agrochemicals and other impurities (UNEP and SEI 2009).

12.3.3 Sprinkler Irrigation

Systems of pressurized irrigation, sprinkler or drip, can improve water efficiency and contribute substantially to improved food production. Sprinkler irrigation is a type of pressurized irrigation that consists of applying water to the soil surface using mechanical and hydraulic devices that simulate natural rainfall (Fig. 12.9). These devices replenish the water consumed by crops or provide water required for softening the soil to make it workable for agricultural activities. The goal of irrigation is to supply each plant with just the right amount of water it needs. Sprinkler irrigation is a method by which water is distributed from overhead by high-pressure sprinklers, sprays, or guns mounted on risers or moving platforms. Today a variety of sprinkler systems ranging from simple hand-move to large self-propelled systems are used worldwide. Use of sprinkler irrigation is practiced in the Americas (13.3 million hectares (Mha)), Europe (10.1 Mha), Asia (6.8 Mha), Africa (1.9 Mha), and Oceania (0.9 Mha) (Kulkarni et al. 2006).

A sprinkler irrigation system typically consists of:

1. A pump unit which takes water from the source and provides pressure for delivery into the pipe system. The pump must be set to supply water at an adequate pressure so that the water is applied at rate and volume adequate to the crop and soil types.
2. Main pipes and secondary pipes which deliver water from the pump to the laterals. In some cases, these pipelines are permanently installed on the soil surface or buried below ground. In other cases, they are temporary and can be moved from field to field. The main pipe materials used include asbestos cement, plastic, or aluminum alloy.
3. The laterals deliver water from the pipes to the sprinklers. They can be permanent, but more often they are portable and made of aluminum alloy or plastic so that they can be moved easily.
4. Sprinklers are water-emitting devices which convert the water jet into droplets. The distribution of sprinklers should be arranged so as to wet the soil surface in the plot as evenly as possible.

A wide range of sprinkler systems is available for small- and large-scale application. Set systems operate with sprinklers in a fixed position. These sprinklers can be moved to water different areas of the field, either by hand or with machinery. Hand-move systems are more labor intensive and may be more suited where labor is available and cheap. On the other hand, mechanically operated systems require a greater capital investment in equipment. Mobile systems minimize labor inputs by operating with motorized laterals or sprinklers, which irrigate and move continuously at the same time (Savva and Frenken 2002).

Table 12.3 Farm irrigation efficiencies for sprinkler irrigation in different climates (the overall efficiency comprises conveyance efficiency, field canal efficiency, and field application efficiency) (FAO 1982)

Climate/temperature	Farm irrigation efficiency
Cool	0.80
Moderate	0.75
Hot	0.70
Desert	0.65

Sprinkler irrigation efficiency is highly dependent on climatic conditions. FAO (1982) proposed the figures of farm irrigation efficiencies provided in Table 12.3 on the basis of climate.

Sprinkler irrigation technology can support farmers to adapt to climate change by making more efficient use of their water supply. This is particularly appropriate where there is (or is expected to be) limited or irregular water supply for agricultural use. The sprinkler technology uses less water than irrigation by gravity and provides a more even application of water to the cultivated plot. Additionally, sprinkler irrigation can reduce the risk of crops freezing due to colder than usual temperatures. More frequent and intense frosts are already impacting on crops as a result of climate change. During the night, the motion of the sprinklers and the application of rain-like water droplets can reduce the stress on crops caused by a sharp decrease in temperature (Snyder and Melo-Abreu 2005).

12.3.3.1 Advantages

One of the main advantages of the sprinkler irrigation technology is more efficient use of water for irrigation in agriculture. Sprinkler systems eliminate water conveyance channels, thereby reducing water loss. Water is also distributed more evenly across crops helping to avoid wastage. The sprinkler irrigation system has also been shown to increased crop yields (Table 12.4) and is suited for most row, field, and tree crops that are grown closely together, such as cereals, pulses, wheat, sugarcane, groundnut, cotton, vegetables, fruits, flowers, spices, and condiments and for cultivating paddy crop (Kundu et al. 1998).

Sprinkler irrigation technology is well adapted to a range of topographies and is suitable in all

Table 12.4 Response of different crops to sprinkler irrigation systems (INCID 1998)

Crops	Water saving %	Yield increase %
Barley	56	16
Cabbage	40	3
Cauliflower	35	12
Chilies	33	24
Cotton	36	50
Groundnut	20	40
Maize	41	36
Onion	33	23
Potato	46	4
Wheat	35	24

types of soil, except heavy clay. Sprinkler systems can be installed as either permanent or mobile fixtures. Sprinklers provide a more even application of water to agricultural land, promoting steady crop growth. Likewise, soluble fertilizers can be channeled through the system for easy and even application. The risk of soil erosion can be reduced because the sprinkler system limits soil disturbance, which can occur when using irrigation by gravity. In addition, sprinkler irrigation can provide additional protection for plants against freezing at low temperatures. Secondary benefits from improved crop productivity include income generation, employment opportunities, and food security.

12.3.3.2 Disadvantages

The main disadvantages associated with sprinkler systems are related to climatic conditions, water resources, and cost. Even moderate winds can seriously reduce the effectiveness of sprinkler systems by altering the distribution pattern of the water droplets. Likewise, when operating under high temperatures, water can evaporate at a fast rate, reducing the effectiveness of the irrigation. Although sprinkler irrigation can help farmers to use water resources more efficiently, this technology relies on a clean source of water and therefore may not be suited to areas where rainfall is becoming less predictable. Implementation costs are higher than that of gravity-fed irrigation systems, and large labor force is needed to move pipes and sprinklers in a nonpermanent system. In some places, such labor may not be available and may also be costly. Mechanized sprinkler irrigation systems have a relatively high energy demand (Savva and Frenken 2002).

12.3.4 Drip Irrigation

Drip irrigation is based on the constant application of a specific and focused quantity of water to soil in the region of feeder roots of crops. The system uses pipes, valves, and small drippers or emitters transporting water from the sources (i.e., wells, tanks, and or reservoirs) to the root area and applying it under particular quantity and pressure specifications. The system should maintain adequate levels of soil moisture in the rooting areas, fostering the best use of available nutrients and a suitable environment for healthy plant roots systems. Managing the exact (or almost) moisture requirement for each plant, the system significantly reduces water wastage and promotes efficient use. Compared to surface irrigation, which can provide 60 % water-use efficiency and sprinkler systems which can provide 75 % efficiency, drip irrigation can provide as much as 90 % water-use efficiency (FAO 2002).

In recent times, drip irrigation technology has received particular attention from farmers, as water needs for agricultural uses have increased and available resources have diminished. In particular, drip irrigation has been applied in arid and semiarid zones as well as in areas with irregular flows of water (or in zones with underground water resources that rely on seasonal patterns such as river flow or rainfall).

Drip irrigation zones can be identified based on factors such as topography, field length, soil texture, optimal tape run length, and filter capacity. Many irrigation system suppliers use computer programs to analyze these factors and design drip systems. Once the zones are assigned and the drip system is designed, it is possible to schedule irrigations to meet the unique needs of the crop in each zone. Recent automatic systems technology has been particularly useful to help control flows and pressure and to identify potential leaks, thereby reducing labor requirements. System design must take into account the effect

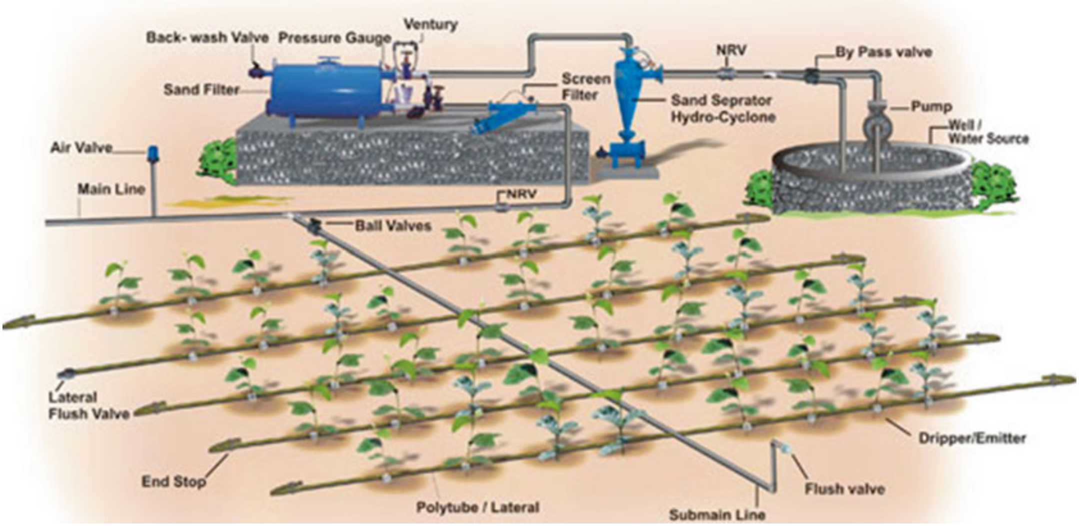

Fig. 12.10 A typical drip irrigation system

of the land topography on water pressure and flow requirements. A plan for water distribution uniformity should be made by carefully considering the tape, irrigation lengths, topography, and the need for periodic flushing of the tape. The design should also include vacuum relief valves into the system (Fig. 12.10).

Drip irrigation technology can support farmers to adapt to climate change by providing efficient use of water supply. Particularly in areas subject to climate change impacts such as seasonal droughts, drip irrigation reduces demand for water and reduces water evaporation losses (as evaporation increases at higher temperatures). Scheduled water application will provide the necessary water resources direct to the plant when required. Furthermore, fertilizer application is more efficient since it can be applied directly through the pipes.

As is the case with a sprinkler system, drip irrigation is more appropriate where there is (or is expected to be) limited or irregular water supply for agricultural use. However, the drip technology uses even less water than sprinkler irrigation, since water can be applied directly to the crops according to plant requirements. Furthermore, the drip system is not affected by wind or rain (as is the sprinkler technology).

12.3.4.1 Advantages

Drip irrigation can help use water efficiently. A well-designed drip irrigation system reduces water runoff through deep percolation or evaporation to almost zero. If water consumption is reduced, production costs are lowered. Also, conditions may be less favorable for the onset of diseases including fungus. Irrigation scheduling can be managed precisely to meet crop demands, holding the promise of increased yield and quality.

Agricultural chemicals can be applied more efficiently and precisely with drip irrigation. Since only the crop root zone is irrigated, nitrogen that is already in the soil is less subject to leaching losses. In the case of insecticides, fewer products might be needed. Fertilizer costs and nitrate losses can be reduced. Nutrient applications can be better timed to meet plants' needs.

The drip system technology is adaptable to terrains where other systems cannot work well due to climatic or soil conditions. Drip irrigation technology can be adapted to lands with different topographies and crops growing in a wide range of soil characteristics (including salty soils). It has been particularly efficient in sandy areas with permanent crops such as citrus, olives, apples, and vegetables. A drip irrigation system can be automated to reduce the requirement for labor.

Fig. 12.11 Fog harvesting

12.3.4.2 Disadvantages

The initial cost of drip irrigation systems can be higher than other systems. Final costs will depend on terrain characteristics, soil structure, crops, and water source. Higher costs are generally associated with the costs of pumps, pipes, tubes, emitters, and installation. Unexpected rainfall can affect drip systems either by flooding emitters, moving pipes, or affecting the flow of soil salt content. Drip systems are also exposed to damage by rodents or other animals. It can be difficult to combine drip irrigation with mechanized production as tractors and other farm machinery can damage pipes, tubes, or emitters.

12.3.5 Fog Harvesting

Fogs have the potential to provide an alternative source of fresh water in dry regions and can be harvested through the use of simple and low-cost collection systems. Captured water can then be used for agricultural irrigation and domestic use. Research suggests that fog collectors work best in locations with frequent fog periods, such as coastal areas where water can be harvested as fog moves inland driven by the wind. However, the technology could also potentially supply water in mountainous areas if the water is present in stratocumulus clouds, at altitudes of approximately 400–1,200 m (UNEP 1997). In addition to Chile, Peru, and Ecuador, the areas with the most potential to benefit include the Atlantic coast of southern Africa (Angola, Namibia), South Africa, Cape Verde, China, Eastern Yemen, Oman, Mexico, Kenya, and Sri Lanka.

Fog harvesting technology consists of a single or double layer mesh net supported by two posts rising from the ground. Mesh panels can vary in size. The ones used by the University of South Africa in a fog harvesting research project measured 70 m^2 (UNISA 2008), whereas in Yemen, a set of 26 small Standard Fog Collectors (SFC) of 1 m^2 were constructed. The material used for the mesh is usually nylon, polyethylene, or polypropylene netting (also known as "shade cloth") which can be produced to various densities capable of capturing different quantities of water from the fog that passes through it (UNEP 1997). The collectors are positioned on ridgelines perpendicular to prevailing wind and capture and collect water when fog sweeps through (Fig. 12.11). The number and size of meshes chosen will depend on the local topography, demand for water, and availability of financial resources and materials. According to FogQuest, the optimal allocation is single mesh units with spacing between them of at least 5 m with additional fog collectors placed upstream at a distance of at least ten times higher than the other fog collector. In South Africa, the university research project arranged several mesh panels together in order to expand the water catchment area and provide greater stability to the structure in windy conditions (UNISA 2008).

The collector and conveyance system functions due to gravity. Water droplets that collect on

Table 12.5 Water collection rates from fog collectors

Project	Total collecting surface (m^2)	Water collected (liters/day)
University of South Africa	70	3,800
Yemen	40	4,500
Cape Verde	200	4,000
Dominican Republic	40	4,000
Eritrea	1,600	12,000

Sources: UNISA (2008), Schemenauer et al. (2004), Wash technology, FogQuest

the mesh run downwards and drip into a gutter at the bottom of the net from where they are channeled via pipes to a storage tank or cistern. Typical water production rates from a fog collector range from 200 to 1,000 l per day, with variability occurring on a daily and seasonal basis (FogQuest). Efficiency of collection improves with larger fog droplets, higher wind speeds, and narrower collection fibers/mesh width. In addition, the mesh should have good drainage characteristics. Water collection rates from fog collectors are shown in Table 12.5.

The dimensions of the conveyance system and storage device will depend on the scale of the scheme. Storage facilities should be provided for at least 50 % of the expected maximum daily volume of water consumed. For agricultural purposes, water is collected in a regulating tank, transferred to a reservoir, and then finally into an irrigation system that farmers can use to water their crops (UNEP 1997).

Drought caused by climate change is leading to reductions in the availability of fresh water supplies in some regions. This is having an impact on agricultural production by limiting opportunities for planting and irrigation. Fog harvesting provides a way of capturing vital water supplies to support farming in these areas. Furthermore, when used for irrigation to increase forested areas or vegetation coverage, water supplies from fog harvesting can help to counteract the desertification process. If the higher hills in the area are planted with trees, they too will collect fog water and contribute to the aquifers. The forests can then sustain themselves and contribute water to the ecosystem, helping to build resilience against drier conditions.

12.3.5.1 Advantages

Atmospheric water is generally clean, does not contain harmful microorganisms, and is immediately suitable for irrigation purposes. In a number of cases, water collected with fog harvesting technology has been shown to meet World Health Organization standards (UNISA 2008). The environmental impact of installing and maintaining the technology is minimal. Once the component parts and technical supervision have been secured, construction of fog harvesting technology is relatively straightforward and can be undertaken on site. The construction process is not labor intensive, only basic skills are required, and, once installed, the system does not require any energy for operation. Given that fog harvesting is particularly suitable for mountainous areas where communities often live in remote condition, capital investment and other costs are generally found to be low in comparison with conventional sources of water supply (UNEP 1997).

12.3.5.2 Disadvantages

Fog harvesting technologies depend on a water source that is not always reliable, because the occurrence of fogs is uncertain. However, certain areas do have a propensity for fog development, particularly, mountainous coastal areas on the western continental margin of South America. Further, calculation of even an approximate quantity of water that can be obtained at a particular location is difficult (Schemenauer and Cereceda 1994). This technology might represent an investment risk unless a pilot project is first carried out to quantify the potential water rate yield that can be anticipated in the area under consideration.

12.3.6 Interventions

12.3.6.1 Research and Development

- Development of crop variants with high water-use efficiency levels such as those capable of regulating stomata closure and opening, etc.
- Exploring structural and technological measures to enhance water-use efficiency with reference to various types of crops, soils, agroclimatic zones, etc.

12.3.6.2 Technologies and Good Practices

- Augmentation of water resources through extensive rainwater harvesting, artificial recharge of groundwater, etc.
- Use of prefabricated water conveyance systems and adoption of ridge and furrow method of irrigation, raised bed method of farming, field bunding, leveling, etc.
- Development of storage structures for off-season use
- Wastewater treatment and its utilization
- Promotion of watershed development and management practices
- Improvement of irrigation efficiency by promoting drip and sprinkler irrigation techniques in place of channel irrigation
- Growing of less water-demanding crops and adopting resource conservation technologies (RCTs) to economize water use
- Adopting mixed cropping and agro-forestry practices for retaining soil moisture and reducing dependency on irrigation
- Intermittent flooding during rice cultivation for aeration of the fields

12.4 Agro-forestry (Adaptation)

Agro-forestry is an integrated approach to the production of trees and of non-tree crops or animals on the same piece of land. The crops can be grown together at the same time, in rotation, or in separate plots when materials from one are used to benefit another. Agro-forestry systems take advantage of trees for many uses: to hold the soil, to increase fertility through nitrogen fixation or through bringing minerals from deep in the soil and depositing them by leaf fall, and to provide shade, construction materials, foods, and fuel. In agro-forestry systems, every part of the land is considered suitable for the cultivation of plants. Perennial, multiple purpose crops that are planted once but yield benefits over a long period of time are given priority. The design of agro-forestry systems prioritizes the beneficial interactions between crops, for example, trees can provide shade and reduce wind erosion. According to the World Agro-forestry Centre, "agro-forestry is uniquely suited to address both the need for improved food security and increased resources for energy, as well as the need to sustainably manage agricultural landscapes for the critical ecosystem services they provide." Agro-forestry is already widely practiced on all continents. Using a 10 % tree cover as threshold, agro-forestry is most important in Central America, South America, and Southeast Asia but also occupies a large amount of land area in Africa.

Generally agro-forestry systems can be categorized into three broad types: agrosilviculture (trees with crops), agrisilvipasture (trees with crops and livestocks), and silvopastoral (trees with pasture and livestock) systems.

Agro-forestry is appropriate for all land types and is especially important for hillside farming where agriculture may lead to rapid loss of soil. The most important trees for incorporating into an agro-forestry system are legumes because of their ability to fix nitrogen and make it available to other plants. Nitrogen improves the fertility and quality of the soil and can improve crop growth. Some of the most common uses of trees in agro-forestry systems are:

- Alley cropping: growing annual crops between rows of trees
- Boundary plantings/living fences: trees planted along boundaries or property lines to mark them well
- Multi-strata: including home gardens and agroforests that combine multiple species and are particularly common in humid tropics such as in Southeast Asia
- Scattered farm trees: increasing number of trees, shrubs, or shaded perennial crops (such as coffee and cocoa) scattered among crops or pastures and along farm boundaries

Any crop plant can be used in an agro-forestry system. When selecting crops, the following criteria should be prioritized:

- Potential for production
- Can be used for animal feed
- Already produced in the region, preferably native to the zone

- Good nutritional content for human consumption
- Can protect the soil
- A lack of competition between the trees and crops

Five stages to the design and implementation of an agro-forestry system are presented in Table 12.6.

Agro-forestry can improve the resilience of agricultural production to current climate variability as well as long-term climate change through the use of trees for intensification, diversification, and buffering of farming systems. Trees have an important role in reducing vulnerability, increasing resilience of farming systems, and buffering agricultural production against climate-related risks. Trees are deep rooted and have large reserves and are less susceptible than annual crops to interannual variability or short-lived extreme events like droughts or floods. Thus, tree-based systems have advantages for maintaining production during wetter and drier years. Second, trees improve soil quality and fertility by contributing to water retention and by reducing water stress during low rainfall years. Tree-based systems also have higher evapotranspiration rates than row crops or pastures and can thus maintain aerated soil conditions by pumping excess water out of the soil profile more rapidly than other production systems if there is sufficient rainfall/soil moisture (Martin and Sherman 1992).

Trees can reduce the impacts of weather extremes such as droughts or torrential rain. For example, a combination of Napier grass and leguminous shrubs in contour hedgerows reduced erosion by up to 70 % on slopes above 10 % inclination without affecting maize yield in central Kenya (Mutegi et al. 2008). Research has also demonstrated that the tree components of agroforestry systems stabilize the soil against landslides and raise infiltration rates (Ma et al. 2009). This limits surface flow during the rainy season and increases groundwater release during the dry season.

Agro-forestry can also play a vital role in improving food security through providing a means for diversifying production systems. By integrating trees in their farms and rangelands, farmers reduce their dependency on a single staple crop or having sufficient grass for their animals. For example, if a drought destroys the annual crop, trees will still provide fruits, fodder, firewood, timber, and other products that often achieve high commercial value. A study of 1,000 farmers from 15 districts in Kenya found that fruit trees contributed 18 % of crop revenue and tea and coffee contributed an additional 29 % of revenue. A study in Zimbabwe concluded that indigenous fruits provided higher returns to labor than annual crop production (Mithoefer and Waibel 2003). A study from Nepal on the impact of agro-forestry on soil fertility and farm income showed that agro-forestry intervention nearly doubled farm productivity and income (Neufeldt et al. 2009).

12.4.1 Advantages

Agro-forestry has a broad application potential and provides a range of advantages, including:

- Agro-forestry systems make maximum use of the land and increase land-use efficiency.
- The productivity of the land can be enhanced as the trees provide forage, firewood, and other organic materials that are recycled and used as natural fertilizers.
- Increased yields. For example, millet and sorghum may increase their yields by 50–100 % when planted directly under *Acacia albida* (FAO 1991).
- Agro-forestry promotes year-round and long-term production.
- Employment creation. Longer production periods require year-round use of labor.
- Protection and improvement of soils (especially when legumes are included) and of water sources.
- Livelihood diversification.
- Provides construction materials and cheaper and more accessible fuel wood.
- Agro-forestry practices can reduce needs for purchased inputs such as fertilizers.

Table 12.6 Five stages to the design and implementation of an agroforestry system

Stage	Basic tasks
Diagnostic	Definition of the land-use system and site selection
	Physical characteristics (including altitude, rainfall, slopes, water supplies, soil condition, visible erosion). This is basic background for evaluating the need for agro-forestry and the local suitability of various techniques
	Current uses of trees and shrubbery. This suggests the kind of subsistence products that an agro-forestry system would be expected to provide
	Sales and purchases of agro-forestry products (including poles, fruit, firewood, fodder, etc.). This provides data for economic analysis and indicates opportunities to replace purchased items or to expand sales by raising agro-forestry products
	Current tree planting (including species, source of seedlings, and intended use). This shows the present state of silvicultural knowledge
	Farmers' perceptions of deforestation and erosion (including any perceived impact on crop yields). This gives a sense of how critical farmers think their problems are and indicates current awareness of agro-forestry relationships
	Land and tree tenure. This shows whether farmers have a right to their trees and therefore whether they have an incentive to plant
	Current yields
	Limiting constraints access to technology and finance, farmer capacities, and markets
	Survey of local knowledge and scope for domestication of wild food and medicinal plants
Design and evaluation	How to improve the system?
	List potential benefits of an agro-forestry system
	List agricultural production needs (meet food security, increase production to meet market demands, and so on)
	Adoptability considerations: social and cultural acceptance; importance of local knowledge, practice, and capacity; as well as equity and gender issues
	Characterize the crops desired by minimum space requirements, water and fertilizer needs, and shade tolerance
	Select the trees, shrubs, or grasses to be used
Planning	If the system is temporary:
	Plan the features of soil erosion control, earthworks, and gully maintenance
	Plan spacing of fruit trees according to final spacing requirements
	Plan a succession of annual or short-lived perennials beginning with the most shade tolerant for the final years of intercropping
	If the system is permanent:
	Plan the proportion of the permanent fruit and lumber trees on the basis of relative importance to the farmer
	Plan the spacing of long-term trees on the basis of final space requirements times 0.5
	Plan succession of annual and perennial understory crops, including crops for soil protection and enrichment
	As large permanent trees grow, adjust planting plan to place shade-tolerant crops in most shady areas
Implementation	On-farm trials of proposed agro-forestry models to analyze impacts of trees on crops, testing harvesting regimes
Monitoring	Ongoing study and analysis of soil nutrition, moisture, and so on
	Watershed design study
	Measure the inputs and outputs of the system (including yields of trees and crops, and labor requirements)
	Survey of land use
	Socioeconomic benefit assessment

Source: Martin and Sherman (1992) and FAO (1991)

12.4.2 Disadvantages

Agro-forestry systems require substantial management. Incorporating trees and crops into one system can create competition for space, light, water, and nutrients and can impede the mechanization of agricultural production. Management is necessary to reduce the competition for resources and maximize the ecological and productive benefits. Yields of cultivated crops can also be smaller than in alternative production system; however, agro-forestry can reduce the risk of harvest failure.

12.4.3 Integrated Crop–Livestock Systems

The annual crops may be rotated with pasture without the destructive intervention of soil tillage (FAO 2011). Practical innovations have harnessed synergies between crop, livestock, and agro-forestry production to improve the economic and ecological sustainability of agricultural systems and at the same time provide a flow of valued ecosystem services. Through increased biological diversity, efficient nutrient recycling, improved soil health, and forest conservation, integrated systems increase environmental resilience and contribute to climate change adaptation and mitigation. They also enhance livelihood diversification and efficiency by optimizing production inputs, including labor. In this way, integrated systems also increase producers' resilience to economic stresses (FAO 2011).

Integrated crop–livestock systems imply a diverse range of integrated ecological, biophysical, and socioeconomic conditions (FAO 2010). They aim to increase profits and sustain production levels while minimizing the negative effects of intensification and preserving natural resources (IFAD 2009). They also have environmental, social, and economic benefits. These systems, which enhance the natural biological processes above and below the ground, represent a synergistic combination that (a) reduces erosion; (b) increases crop yields, soil biological activity, and nutrient recycling; (c) intensifies land use and improving profits; and (d) can therefore help reduce poverty and malnutrition and strengthen environmental sustainability (IFAD 2009).

As climate changes, the resilience and adaptive capacity of agricultural production systems and agricultural landscapes will become more important. To become more resilient and better able to adapt to changing conditions, crop production systems will need to rely more on ecological processes that produce positive feedbacks on sustainability and production and ensure improved provision of all ecosystem services (FAO-PAR 2011). Progress in this area could be made by adopting existing agricultural practices that have already been proven to have multiple benefits for food security and environmental health.

12.5 Ecological Pest Management

12.5.1 Key Issues

- Efficient, safe, and environmentally sound methods of pest management
- Incentivizing research, commercial production, and marketing of biopesticides
- Developing insect forecasting models
- Decision and information support systems for pest and disease surveillance
- Institutional mechanism for quick response in case of disaster

Ecological Pest Management (EPM) is an approach to increasing the strengths of natural systems to reinforce the natural processes of pest regulation and improve agricultural production. Also known as Integrated Pest Management (IPM), this practice can be

> defined as the use of multiple tactics in a compatible manner to maintain pest populations at levels below those causing economic injury while providing protection against hazards to humans, animals, plants and the environment. IPM is thus ecologically-based pest management that makes full use of natural and cultural processes and methods, including host resistance and biological control. IPM emphasizes the growth of a healthy crop with the least possible disruption of agro-ecosystems, thereby encouraging natural pest control mechanisms. Chemical pesticides are used only where and when these natural methods fail to keep pests below damaging levels.

EPM is a biotechnology belonging to the denominated "clean" technologies which combines the life cycle of crops, insects, and implicated fungi, with natural external inputs (i.e., biopesticides) that allows a better guarantee of good harvesting even in difficult conditions of pests and diseases that emerge with the temperature and water level changes (increase of relative atmospheric humidity and runoff) typical of climate change. Thus, it is a biotechnology for facing uncertainty caused by climate change.

EPM contributes to climate change adaptation by providing a healthy and balanced ecosystem in which the vulnerability of plants to pests and diseases is decreased. By promoting a diversified farming system, the practice of EPM builds farmers' resilience to potential risks posed by climate change, such as damage to crop yields caused by newly emerging pests and diseases.

The basis of this natural method of controlling pests is the biodiversity of the agroecological system. This is because the greater the diversity of natural enemy species, the lower the density of the pest population, and as diversity of natural enemy species decreases, pest population increases.

The key components of an EPM approach are:

12.5.2 Crop Management

Selecting appropriate crops for local climate and soil conditions. Practices include:

- Selection of pest-resistant, local, native varieties and well-adapted cultivars
- Use of legume-based crop rotations to increase soil nitrate availability, thereby improving soil fertility and favorable conditions for robust plants that better face pests and diseases
- Use of cover crops, such as green manure to reduce weed infestation, disease, and pest attacks
- Integration of intercropping and agro-forestry systems
- Use of crop spacing, intercropping, and pruning to create conditions unfavorable to the pests

12.5.3 Soil Management

Maintaining soil nutrition and pH levels to provide the best possible chemical, physical, and biological soil habitat for crops. Practices include:

- Building a healthy soil structure according to the soil requirements of the different plants (such as deep/shallow soil levels or different mineral contents).
- Using longer crop rotations to enhance soil microbial populations and break disease, insect, and weed cycles.
- Applying organic manures to help maintain balanced pH and nutrient levels. Adding earthworm castings, colloidal minerals, and soil inoculants will supplement this. Microbes in the compost will improve water absorption and air exchange.
- Soil nutrients can be reactivated by alleviating soil compaction.
- Reducing soil disturbance (tillage) – undisturbed soil with sufficient supply of organic matter provides a good habitat for soil fauna.
- Keeping soil covered with crop residue or living plants.

12.5.4 Pest Management

Using beneficial organisms that behave as parasitoids and predators. Practices include:

- Releasing beneficial insects (predators) and providing them with a suitable habitat
- Managing plant density and structure so as to deter diseases
- Cultivating for weed control based on knowledge of the critical competition period
- Managing field boundaries and in-field habitats to attract beneficial insects and trap or confuse insect pests

IPM strategies can exist at various levels of integration. Note that integration at all four levels is not common:

- Control of a single pest on a particular crop
- Control of several pests on the same crop
- Several crops (and non-crop species) within a single production unit (farm)

- Several farms in a region (area-wide pest management)

These practices, if well implemented, result in systems that are:

- Self-regulating, maintaining populations of pests within acceptable boundaries
- Self-sufficient, with minimal need for "reactive" interventions
- Resistant to stresses such as drought, soil compaction, and pest invasions
- Capable of recuperating from stresses

Worldwide public attention has been focused on the importance of EPM since the United Nations Conference on Environment and Development held in Rio de Janeiro in June 1992. The blueprint for action prepared by the Conference (Agenda 21) recognized pesticide pollution as a major threat to human health and the environment worldwide and identified IPM as a key element in sustainable agricultural development.

Pesticide consumption in India has increased over time, and its injudicious use has created problems like development of resistant strains in insects and plant pathogens; resurgence of pest species; direct exposure to the applicator; destruction of parasites, predators, and other beneficial organisms; and accumulation of pesticide residues in agricultural commodities, water, air and soil, etc. Pesticide residues in feed and water affect livestock health due to direct and indirect exposure in the course of pest control measures. Strategies suggested under this intervention have to primarily focus on the establishment of decision and information support systems for pest and disease surveillance, demonstration of best practices, and quick response mechanism that are at par with the norms to deal with other disasters or natural calamities.

12.5.5 Advantages

With the EPM approach, farmers can avoid the costs of pesticides as well as the fuel, equipment, and labor used to apply them. A 22-year trial comparing conventional and organic corn/soybean systems found that organic farming approaches for these crops use an average of 30 % less fossil energy (Pimentel et al. 2005). Although this can cause a slight drop in productive performance, the risk of losing an entire crop is reduced dramatically.

There are also reports that production levels have increased when there has been a reduction in the use of pesticides. This is the case when there are specific controllers for a determined pest, for example, in West Africa the introduction of the wasp has been a spectacular control of the slug of cassava, thus saving the staple food crop for millions of Africans.

12.5.6 Disadvantages

There are very strong pests for which the "biological control" has not yet been identified (i.e., an insect that destroys it). When these pests emerge, it is common for producers to turn to pesticides. EPM is not easy to implement and requires substantial knowledge and monitoring for the combined components of the system to produce success. Perhaps the biggest drawback to the EPM approach is that biological control is not a "quick fix." In most cases, biological control will take several years to successfully establish a population and begin making a significant contribution. In addition, no single biological control works in every situation. A control that works well in one soil type, for example, may not work at all in another soil type. In the long run, more than one type of biological control may have to be used to achieve uniform control across a variety of different situations and land types.

12.5.7 Interventions

12.5.7.1 Research and Development

- Providing site-specific weather data to help researchers run predictive pest models and for farmers to make informed decisions on pest management.
- Research on pest/insect–crop–weather interactions for developing simple operational and

predictive models that can be used in agro-advisory services.

- Integrate biotechnology with traditional agricultural practices and metabolomic and bioinformatics systems to design novel insecticide molecules for studying interactions with the DNA and protein models.
- Develop new biopesticides and technologies on pest management through sterile insect techniques, new botanical, semiochemicals (repellents, pheromones, allomones, etc.), and endophytic microbial metabolites for pest control, transgenic insects, pests, and disease forecasting.

12.5.7.2 Technologies and Practices

- Develop effective surveillance systems for invasive species based on semiochemicals.
- Streamlining the flow of information of pest surveillance and livestock diseases to reduce response time between detection and action to manage and prevent pests and diseases.
- Promotion of bio-intensive integrated pest management at large scale.
- Strengthening the existing network of veterinary health support services with particular emphasis on preventive healthcare services including immunization.
- Plant protection measures to be tailored to meet the threat to crops and farm animals arising from the outbreak of vector-borne diseases.

12.6 Livestock Adaptation

Adaptation for pasture-grazing livestock includes changes in the use and maintenance of pastures and in the mix of livestock breeds (Easterling et al. 2007).

Climate change is having substantial effects on ecosystems and the natural resources upon which the livestock sector depends. Climate change will affect the sector directly, through increased temperature, changes in the amount of rainfall, and shifts in precipitation patterns. Indirect impacts will be experienced through modifications in ecosystems, changes in the yields, quality and type of feed crops, possible increases in animal diseases, and increased competition for resources.

12.6.1 Sector Trends

Global production of meat, milk, and eggs has rapidly expanded during the last decades in response to growing demand for livestock products. This increase in demand, which has been particularly strong in developing regions, has largely been driven by expanding populations and increasing incomes. For example, between 1960 and 2005, annual per capita consumption of meat has more than tripled, consumption of milk almost doubled, and per capita consumption of eggs increased fivefold in the developing world (Fig. 12.12).

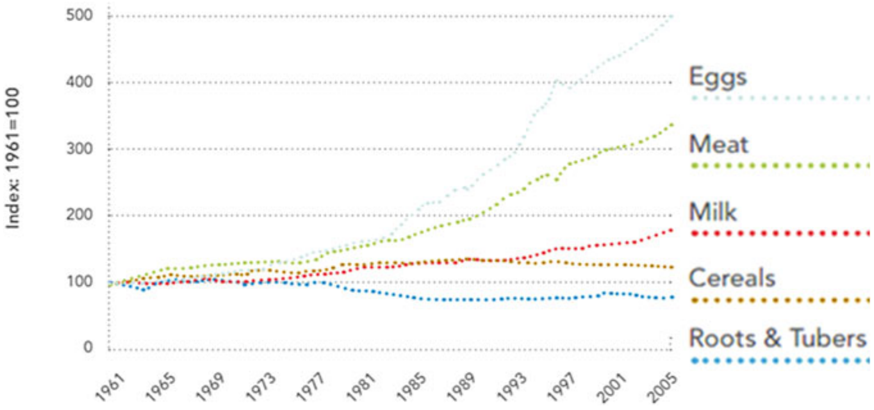

Fig. 12.12 Per capita consumption of major food items in developing countries (FAO 2009)

Excluding Brazil and China, per capita meat consumption in developing countries is expected to increase to 26 kg in 2030 and 32 kg in 2050. In terms of future consumption, it is projected that a marked gap will continue to exist between developed and developing countries. This gap indicates that there is scope for further growth in the livestock sector. Driven by demand, global production of meat is projected to more than double, from 229 million tons in 1999/2001 to 465 million tons in 2050. Milk production is expected to increase from 580 to 1,043 million tons (FAO 2006).

Livestock make a necessary and important contribution to global calorie and protein supplies. However, livestock need to be managed carefully to maximize this contribution. While livestock products are not absolutely essential to human diets, they are valued and they will continue to be consumed in increasing amounts. Meat, milk, and eggs in appropriate amounts are valuable sources of complete and easily digestible protein and essential micronutrients.

12.6.2 Adaptation Needs: Climate-Resilient Livestock

Climate-resilient adaptation options deemed suitable for land-based systems, along with their capacities to satisfy multiple climate-resilient objectives, are listed in Table 12.7.

Table 12.7 Summary of CRA practices and technologies for land-based systems

Practices and technologies	Impact on food security	Effectiveness of adaptation
Grazing management	+/–	+
Pasture management	+	
Animal breeding	+	++
Animal and herd management	+	++
Animal disease and health	++	++
Supplementary feeding	+	+
Vaccines against rumen archaea	++	
Warning systems	++	+
Weather-indexed insurance		+
Agro-forestry practices	++	++

Adaptation potential: + = low; ++ = medium

12.6.3 Livestock Disease Management

Livestock systems in developing countries are characterized by rapid change, driven by factors such as population growth, increases in the demand for livestock products as incomes rise, and urbanization. Climate change is adding to the considerable developmental challenges posed by these drivers of change. The increasing frequency of heat stress, drought, and flooding events could translate into the increased spread of existing vector-borne diseases and macro-parasites, along with the emergence of new diseases and transmission models (IFAD 2002). Appropriate sustainable livestock management practices are required so that livestock keepers can take advantage of the increasing demand for livestock products (where this is feasible) and protect their livestock assets in the face of changing and increasingly variable climates.

Livestock diseases contribute to an important set of problems within livestock production systems. These include animal welfare, productivity losses, uncertain food security, loss of income, and negative impacts on human health. Livestock disease management can reduce disease through improved animal husbandry practices. These include: controlled breeding, controlling entry to farm lots, and quarantining sick animals and through developing and improving antibiotics, vaccines and diagnostic tools, evaluation of ethno-therapeutic options, and vector control techniques.

Livestock disease management is made up of two key components:

- Prevention (biosecurity) measures in susceptible herds
- Control measures taken once infection occurs

The probability of infection from a given disease depends on existing farm practices (prevention) as well as the prevalence rate in host populations in the relevant area. As the prevalence in the area increases, the probability of infection increases.

12.6.3.1 Prevention Measures

Preventing diseases entering and spreading in livestock populations is the most efficient and cost-effective way of managing disease. While many approaches to management are disease specific, improved regulation of movements of livestock can provide broader protection. A standard disease prevention program that can apply in all contexts does not exist. But there are some basic principles that should always be observed. The following practices aid in disease prevention:

- Elaboration of an animal health program.
- Selection of a well-known, reliable source from which to purchase animals, one that can supply healthy stock, inherently vigorous and developed for a specific purpose. New animals should be monitored for disease before being introduced into the main flock.
- Good hygiene including clean water and feed supplies.
- Precise vaccination schedule for each herd or flock.
- Observe animals frequently for signs of disease, and if a disease problem develops, obtain an early, reliable diagnosis and apply the best treatment, control, and eradication measures for that specific disease.
- Dispose of all dead animals by burning, deep burying, or disposal pit.
- Maintain good records relative to flock or herd health. These should include vaccination history, disease problems, and medication.

12.6.3.2 Surveillance and Control Measures

Disease surveillance allows the identification of new infections and changes to existing ones. This involves disease reporting and specimen submission by livestock owners, village veterinary staff, and district and provincial veterinary officers. The method used to combat a disease outbreak depends on the severity of the outbreak. In the event of a disease outbreak, the precise location of all livestock is essential for effective measures to control and eradicate contagious viruses. Restrictions on animal movements may be required as well as quarantine and, in extreme cases, slaughter.

The major impacts of climate change on livestock diseases have been on diseases that are vector-borne. Increasing temperatures have supported the expansion of vector populations into cooler areas. Such cooler areas can be either higher altitude systems (e.g., livestock tick-borne diseases) or more temperate zones (e.g., the outbreak of bluetongue disease in Northern Europe). Changes in rainfall pattern can also influence an expansion of vectors during wetter years and can lead to large outbreaks. Climate changes could also influence disease distribution indirectly through changes in the distribution of livestock. Improving livestock disease control is therefore an effective technology for climate change adaptation.

12.6.3.3 Advantages

Benefits of livestock disease prevention and control include: higher production (as morbidity is lowered and mortality or early culling is reduced) and avoided future control costs. When farmers mitigate disease through prevention or control, they benefit not just themselves but any others at risk of adverse outcomes from the presence of disease on that operation. At-risk populations include residents, visitors, and consumers. The beneficiaries might also include at-risk wildlife populations surrounding the farm that may have direct or indirect contact with livestock or livestock-related material.

12.6.3.4 Disadvantages

Management options may interact, so the use of one option may diminish the effectiveness of another. Another critical issue is the long-term sustainability of currently used strategies. Chemical intervention strategies such as antibiotics or vaccines are not biologically sustainable. Animals develop resistance to drugs used to control certain viruses, and with each new generation of vaccine, a new and more virulent strain of the virus can arise (FAO 2003). Small-scale producers may be negatively affected by livestock disease management if the full cost of the disease management program is directly passed onto them with no subsidy from the government (FAO 2003).

Modeling disease outbreaks and spread can provide valuable information for the development of management strategies. Modeling involves studying disease distribution and patterns of spread to determine the scale of a problem. This information is used to develop a model that can predict the spread of disease. Disease modeling requires prior knowledge of animal population distributions and ecology, diseases present, and methods of disease transmission. Modeling can be used to assess potential disease impacts and develop contingency plans.

Geographic Information System (GIS) software can play a key role in livestock disease management. The main advantage of GIS software is not just that the user can see how a disease is distributed geographically, but also that an animal disease can be viewed against other information (e.g., maps that show the possible impacts of climate change on rainfall patterns, crop yields, and flooding). The disease presence can then be related to these factors and more easily appreciated visually. This is important in relation to managing and responding to the changes in distribution of diseases due to changing climate. The role of indigenous knowledge in livestock disease management under climate change has been shown, in certain cases, to be cost-effective, sustainable, environmental friendly, and practical. Practices include:

- Utilization of local plant remedies for prevention and cure of diseases.
- Avoiding certain pastures at particular times of the year and not staying too long in one place to avoid parasite buildup.
- Lighting smoke fires to repel insects, especially tsetse flies.
- Mixing species in the herd to avoid the spread of disease.
- Avoiding infected areas or moving upwind of them, spreading livestock among different herds to minimize risks, and quarantining sick animals.
- Selective breeding. As an example from the arid south of Zambia, restocking and promoting the rearing of drought-tolerant goat breeds are adaptive measures already being undertaken.

12.6.4 Selective Breeding via Controlled Mating

Genetic makeup influences fitness and adaptation and determines an animal's tolerance to shocks such as temperature extremes, drought, flooding, pests, and diseases. Adaptation to harsh environments includes heat tolerance and an animal's ability to survive, grow, and reproduce in the presence of poor seasonal nutrition as well as parasites and diseases. Selective breeding is a technology that aims to improve the value of animal genetic diversity. This technology can be applied to all types of livestock, including cattle, sheep, and goats. As developments have been made over time in improving measurement techniques and methods for estimating an animal's genetic potential, the power and effectiveness of selective breeding as a tool has also increased. Over the last half century, it has helped achieve dramatic improvements in the productivity of livestock species as well as improvements in the health and welfare of livestock and other animals.

Selective livestock breeding is the systematic breeding of animals in order to improve productivity and other key characteristics. Various methods for selective breeding exist, from high-tech and costly processes such as in vitro fertilization or genetic engineering to more simple low-cost techniques that rely on the selection and controlled mating of animals based on observable characteristics. Key breeding traits associated with climate change resilience and adaptation include thermal tolerance, low-quality feed, high kid survival rate, disease resistance, good body condition, and animal morphology. In general, developing countries have a weak capacity for high-tech breeding programs to increase livestock adaptation (IFAD 2002). Therefore, programs based on controlled mating methods are likely to be more appropriate. These programs usually do not produce immediate improvements. Improvements are usually not seen for at least one growing season, so a livestock producer must be able to incorporate long-term planning into production management strategies. Such measures could include

(1) identifying and strengthening local breeds that have adapted to local climatic stress and feed sources and (2) improving local genetics through cross-breeding with heat- and disease-tolerant breeds.

There are three main approaches to selective breeding:

12.6.4.1 Outcrossing

Mating two animals that are unrelated for at least 4–6 generations back is called an outcross. This method works best when the genetic variation for a trait is high. When dominant genes are the desirable ones, outcrossing works perfectly well. One of the best advantages of outcrossing is that it hides detrimental traits by keeping them recessive. Outcrossing improves fitness traits such as reproductive ability, milk production, kid survivability, and longevity.

12.6.4.2 Linebreeding

Linebreeding involves mating-related animals like half brother/half sister, cousins, aunt/nephew, and other more distant relationships. This is usually done to capitalize on a common outstanding ancestor who appears in recent generations of the pedigree. There is a higher degree of uniformity with linebreeding than in outcrossing and a reduced possibility of harmful genetic defects than inbreeding.

12.6.4.3 Inbreeding

This breeding method involved mating directly related animals, like mother/son, father/daughter, and full brother/full sister (full siblings). This method is used generally to create uniformity and prepotency (the ability of this process to continue) and to force out latent weaknesses from the gene pool. However, recessive genes are more of a factor than dominant genes in genetic faults, so there is a high risk producing kids with problems. Inbreeding reduces the pool of available genes and can cause some lines to become extinct. Fitness traits are especially at risk with this breeding scheme.

Selective breeding through controlled mating enables farmers to breed animals that are more resistant to the impacts of climate change, such as sudden changes in temperature, prolonged droughts, or the appearance of new diseases. It can reduce mortality rates, increase fertility rates, and can also be used to improve the quality of livestock products such as milk and fiber. As a result, livestock producers are at a lower risk from losing animals to climate change impacts, and they are also able to diversify their income-generating activities by capitalizing on higher-quality dairy or fiber production.

12.6.4.4 Advantages

The specific advantages of selective breeding through controlled mating include low input and maintenance costs once the strategy is established and permanence and consistency of effect. In addition, controlled mating can preserve local and rare breeds that could be lost as a result of climate change-related disease epidemics.

12.6.4.5 Disadvantages

One of the main limitations of this technology is that selective breeding of certain genes can run the risk of reducing or removing other genes from the overall pool, a process which is irreversible. This can create new weaknesses among animals, particularly with the emergence of a new pest or disease. Depending on the animal traits chosen, selective breeding may not always lead to higher productivity rates.

12.6.5 Early Warning Systems and Insurance

The use of weather information to assist rural communities in managing the risks associated with rainfall variability is a potentially effective (preventative) option for climate change adaptation. Livestock insurance schemes that are weather indexed (i.e., policy holders are paid in response to “trigger events” such as abnormal rainfall or high local animal mortality rates) may also be effective where preventative measures fail (Skees and Enkh-Amgala 2002).

12.7 Energy Adaptation

The adaptation strategies in energy sector include:

- Exploiting new and renewable energy sources, especially solar energy. Solar power (photovoltaic or solar heaters) (Fig. 12.13), wind, and geothermal energy are all sources of energy that are available today for both large and small applications. They are particularly suitable for remote rural areas.
- Initiating and developing projects that promote the use of alternative and or non-wood energy sources (e.g., biogas and fuel-saving stoves).
- Increasing awareness of the effect of pollution on the environment through information, education, and communication (IEC), with a focus on energy use and environmental education.
- Improvement and increase in clean thermal power generation.
- Protection of hydropower water catchments.
- Increase in availability of biomass resources. Improvement of biomass to increase energy conversion efficiency.
- End-use energy efficiency programs.
- Integrated approach to renewable energy for farming systems.

Non-food crops such as biofuels present opportunities for crop diversification and increased income should also be considered, albeit with caution since they compete with food crops for land, nutrients, and water. Biofuels produce low greenhouse gas emissions by recycling carbon dioxide extracted from the atmosphere. Besides mitigating the impacts of climate change, biofuels have the economic and strategic advantage of replacing fossil fuels (Raswant et al. 2008). Due to their high economic returns with minimum investment, biofuels are seen by smallholder farmers as a viable alternative to labor-intensive and low-yielding cereals. Plants such as jatropha are becoming popular among smallholder farmers in eastern Africa (e.g., Ethiopia) and West Africa (e.g., Mali). However, little information on the productivity of biofuels in water-stressed conditions is available, and more research is needed.

Other crops such as sugarcane, soybean, and maize can also be used as biofuels, but the current global food crisis and escalating prices discourage conversion of food crops to biofuel. Concern over the diversion of food crops to biofuel has placed the issue at the center of debate concerning future options for biofuel (Connor and Hernández 2009). An important consideration, however, is that some biofuel crops are drought resistant and can even be grown on degraded land, hence offering another advantage. The rehabilitation of degraded lands, especially on the vast semiarid environ-

Fig. 12.13 Field filled with solar panels

ments of Sub-Saharan Africa (SSA), could be a boon to many smallholder farmers. The combination of modern breeding and transgenic techniques could result in greater achievements in biofuel crops than those of the green revolution in food crops and in far less time (Ragauskas et al. 2006). There exists some doubt, however, about the long-term negative impact of these crops on soils and human health. Countries such as Burkina Faso are already growing transgenic cotton, vegetables, and potatoes, but the jury is still out on this sensitive issue. One advantage of developing transgenic crops is that they can produce in a very short time and hence cope with low rainfall conditions.

12.8 Early Warning Systems

An Early Warning System (EWS) is a set of coordinated procedures through which information on foreseeable hazards is collected and processed to warn of the possible occurrence of a natural phenomenon that could cause disasters. These systems are acquiring more importance in view of increased climate variability and the ability to implement them has become fundamental for improving capacity to adapt to climate change.

There are two types of EWS:

- Centralized systems implemented by national government bodies. The ministry of defense or another appropriate government entity is responsible for implementing hazard warning and response activities.
- Decentralized community systems, usually operated by a network of volunteers employing simple equipment to monitor meteorological conditions and operate radio communication networks.

Operators of decentralized community meteorological stations report the information to a local forecasting center where the data is analyzed and then communicated back to the community network. The demand for community-led systems is increasing due to lower operational costs and the need for local forecasting and monitoring of climate variability and potential disasters.

The following are the main implementation stages of a decentralized community system:

- Establishing an organizing committee (leaders of the community and civil society, NGOs, representatives of local authorities, and the private sector)
- Creating and analyzing information: building and installing measuring instruments, carrying out forecasts
- Producing a participatory emergency and contingency plan
- Implementing a communication system: early warnings, dissemination of prevention, mitigation and adaptation measures

Increased frequency and intensity of extreme weather events, prolonged drought and processes of desertification, longer periods of heavy rainfall, and increased risk of flooding are just some of the impacts of climate change affecting the world's poorest populations (IPCC 2007). EWS technology designed as a climate change adaptation strategy must therefore be capable of forecasting a number of climatic events that correspond to different time scales:

- Three to four months of advance warning of a drought
- Two to three weeks of advance warning of freezing weather conditions and monsoons
- A few hours of advance warning of torrential rain, hail, and floods

This technology contributes to the climate change adaptation and risk reduction process by improving the capacity of communities to forecast, prepare for, and respond to extreme weather events and thereby minimize damage to infrastructure and social and economic impacts, such as loss of livelihoods.

12.8.1 Advantages

- Introduction of hazard-related and disaster management concepts into community-level planning processes
- Exchange of information of a social or legal nature, in addition to climatic information, through the established communication network

- Facilitation of decision-making in political organizations
- Creation and improvement of a structure that incorporates different stakeholders involved in drawing up specific action plans

12.8.2 Disadvantages

The majority of EWSs were established to prevent or reduce the impacts of climate-related disasters (such as floods and hurricanes). By comparison, the capability of these systems to forecast droughts, extreme colds, and Indian summers has been less effective. Droughts are particularly distinguishable from other extreme weather events in that they begin slowly and gradually and are less “obvious” at the outset. In addition, drought can last extended periods of time and affect extensive areas. Given these complexities, EWSs should be complemented with historical data on droughts, along with available climatological, hydrological, physical, biological, and socioeconomic statistics. Only by combining these data can the complex causes of droughts be better understood and different scenarios modeled with the aim of developing prognoses (such as the probable start date of the rainy season or possible variations in rainy and dry seasons) to be disseminated via appropriate communication channels.

12.9 Crop Insurance Schemes

12.9.1 Key Issues

- Developing various models for risk assessment
- Designing user-friendly decision support systems to help assess risks and develop region-specific contingency plans
- Strengthening existing risk cover mechanism under NAIS and weather-based crop insurance scheme
- Implementing region-specific contingency plans based on vulnerability and risk scenarios

Agricultural insurance is an important mechanism by which risks to agricultural output and income can be addressed. Crop insurance incentivizes farmers to adopt innovative options by spreading the risks over space and time. It also stabilizes farm incomes, thereby enabling farmers to repay debts, which not only preserve the viability of formal financial institutions but also save huge government expenditures incurred in writing-off agricultural loans. Deficiencies in the existing framework of assessment of crop damage and prompt settlement of claims need to be addressed so that a disaster mode of operational efficiency is institutionalized. Research and development activities for developing new insurance products in the light of new risks emerging from climate change also need to be taken up as a medium- to long-term strategy. An effective design and efficient implementation mechanism is required to ensure timely benefits especially to the small and marginalized farmers.

Over the last 40 years, natural catastrophes have caused a sevenfold increase in economic losses (Dlugolecki 2004). Therefore, to address such risks, an effective insurance system is needed that meets the following criteria:

- Affordable and accessible to all rural people
- Compensation for income losses to protect consumption and debt repayment capacity
- Practical to implement, given potential limits on data availability
- Can be provided by the private sector with little or no government subsidies
- Avoids the problems of moral hazard and adverse selection

Effective crop insurance schemes should be evolved to help the farmers in reducing the risk of crop failure due to these events. Both formal and informal, as well as private and public, insurance programs need to be put in place to help reduce income losses as a result of climate-related impacts. However, information is needed to frame out policies that encourage effective insurance opportunities. Micro-finance has been a success among rural poor, including women. Low-cost access to financial services could be a boon for vulnerable farmers. Growing network of mobile telephony could further speed up SMS-based banking services and help the farmers in having better integration with financial institutions. However, compared to micro-finance, micro-insurance innovations and availability are limited. There is a need to develop sustainable insurance system, while the rural poor are to be educated about availing such opportunities.

12.9.2 Interventions

12.9.2.1 Research and Development

- Developing various models for risk assessment to assess the magnitude of risk exposure and availability of supportive infrastructure including resources in case of climate variability and extreme events
- Developing innovative and new generation agricultural insurance products, such as weather index-based insurance, livestock insurance, etc.
- Developing strategies to deal with emerging risks due to climate change such as high intensity rain, heat waves, depletion of groundwater, water contamination, etc.
- Designing user-friendly decision support systems to help assessing risks and develop region-specific contingency plans

12.9.2.2 Technologies and Practices

- Assessing availability of appropriate technologies and their backstopping support system that has long-term effect on reduction of risk mitigation
- Use of crop-weather forecast models to aid field-based planning and operational activities by both farmers and governing bodies

12.10 Livelihood Diversification

12.10.1 Key Issues

- Mitigating risks by supplementing income from off-farm activities
- Crop diversification
- Crop–livestock–fisheries farming system

Livelihood diversification plays a major role in providing options of supplementing income from core agricultural activities through on-farm or off-farm activities, mitigating risks by providing additional support to agricultural income under conditions of climatic and non-climatic stresses, supporting farm-based investments for better productivity, and through income generated by alternate livelihood options. The strategies under this dimension would aim to promote diversification of agriculture into other high-value crops and horticulture; research, development, and extension of crop–livestock farming systems; and increasing focus and development of approaches like sericulture, agro-forestry, crop-fish farming, etc.

12.10.2 Interventions

12.10.2.1 Research and Development

- Development of high productive horticultural crops, namely, fruits, vegetables, aromatic and medicinal plants, and spices and plantation crops (e.g., coconut, areca nut, cashew, cocoa, etc.)
- Conducting research on risks to specific livelihoods for understanding the changing nature of risk due to climatic and non-climatic stresses (e.g., changes in climatic variables, trade patterns, market prices, etc., can guide farmers regarding investments in specific crops)
- Development of decision support system for integrating market information to improve production and trade of horticultural/dairying/fisheries products
- Extending research on resource-conserving technologies (RCT) in the domain of crop production and livestock management

12.10.2.2 Technologies and Practices

- Penetration of technologies such as micropropagation; integrated nutrient, water, and pest management; organic farming; and immunodiagnostic techniques for detection of diseases and to improve the productivity of horticultural crops
- Strengthening technologies and practices that assist in food processing such as value addition and cold storage for horticulture/dairying/fisheries products

- Adopting region-specific silvicultural and farming practices to optimize food production, carbon sequestration, and biodiversity conservation
- Refining package of practices for crop-fish farming using locally available resources and resource-efficient practices that reduce input requirements supported by appropriate policy instrument to reduce investments and cost input in terms of feed, manpower, and infrastructure
- Developing and strengthening low tunnel/polyhouse farming under controlled condition to sustain livelihood from small landholdings

12.11 Access to Information

12.11.1 Key Issues

- Minimizing information asymmetry through ICT-based systems
- Public–private partnership to develop technology-based solution for providing farmers with information on price discovery, commodity arrivals, mandi prices, etc.
- Building an ICT-enabled knowledge management network
- To create, manage, and develop national resource portal

Effective communication approaches are critical to help farmers adapt to climate change as weather becomes more erratic and less predictable. Fresh strategies for management of information may be required to sustain production levels. This dimension is crosscutting in nature, having implications at all levels in the agricultural production system as well as for all the other key dimensions. At the crop level, the focus needs to be on upscaling the efforts to link the public and private partners with the research institutions so that the laboratory results can get commercialized quickly. At the level of the farm, focus needs to be on enhancing awareness of farmers as well as the developmental agencies with the latest scientific research, market information, and policy initiatives so that they are empowered to take informed decisions for maximizing farm productivity. At a larger scale, at the food system level, technological and infrastructural research along with interventions required to enhance the adaptive capacity for ensuring food security in the wake of climate change must be investigated.

12.11.2 Interventions

12.11.2.1 Research and Development

- Minimizing information asymmetry through focused attention on developing ICT-based systems and methodologies for quick and timely dissemination of information to rural and remote end users

12.11.2.2 Technologies and Practices

- Forging public–private partnership to develop technology-based solutions for providing farmers with information on price discovery, commodity arrivals, mandi prices, etc.
- Partnering with civil society organizations for large-scale deployment of technology for communicating climate change risks to bring about behavioral changes for adopting good agricultural practices
- Preparation of crop-/commodity-specific advisories for different soil and climatic characteristics for the use of farmers to adopt specific packages suitable to weather conditions

12.12 Credit Support

12.12.1 Key Issues

- Developing new forms of credit assessment and risk management systems
- Promoting micro-finance
- Developing mechanisms to enhance the flow of credit to critical infrastructure
- Upscaling the Kisan Credit Card Scheme (KCCS)
- Designing customized credit policies and programs to mitigate risks

Free, untied, and timely credit support to farmers is essential for sustaining farm productivity, especially when it comes to small and marginal farmers. Easy and timely financial incentives and credit (and insurance) packages provided to farmers can help in adoption of improved management practices including resource conservation technologies, agro-diversification, postharvest value addition processes, etc., which would contribute to reducing risks and enhancing farm incomes. This dimension emphasizes efforts to augment the flow of credit to agriculture, alongside exploring new innovations in product design and methods of delivery, through better use of technology and related processes. Facilitating delivery through processors, input dealers, NGOs, self-help groups (SHGs), etc., would help in providing access to credit to the resource poor farmers, especially the small and marginalized farmers, to help them to manage the additional risks from climate change in a sustainable manner.

12.12.2 Interventions

12.12.2.1 Research and Development

- Research on credit assessment and risk management systems.
- Designing customized credit plans and programs to mitigate risks and support higher productivity and production in drought- and flood-prone areas.
- Designing innovative schemes and products which recognize the varied nature of agribusiness and supply chains for different farming systems, food systems, and communities.

12.12.2.2 Technologies and Practices

- Adoption of a customized approach by financial institutions to cater to specific agricultural credit risks and needs of different agricultural sectors and regions
- Creating credit flow for conservation farming, agricultural diversification, and value-added activities
- Developing credit plans with higher component of direct finance and with a special thrust on small and marginal farmers so as to reduce their dependence on informal credit institutions and money lenders
- Providing financial support/incentives to farmers to enable investment/adoption of relevant technologies to overcome climate-related stress
- Upscaling the Kisan Credit Card Scheme (KCCS) to cover all eligible farmers

12.13 Markets

12.13.1 Key Issues

- To formulate market-aligned research and development programs
- Improving supply chain efficiency
- Creation of new market infrastructure
- Supporting community partnerships in developing food and forage banks
- Strengthening access to quality and timely inputs by farmers for mitigating risks

Inadequate marketing infrastructure, presence of large number of intermediaries, lack of market information and intelligence, and inadequate storage facilities result in huge postharvest losses in the food supply chain. Some of the major initiatives that are to be taken up under this dimension include reducing quantitative as well as qualitative losses across the supply chain; creating market-aligned production systems; strengthening climate-resilient postharvest management, storage, and marketing and distribution system; strengthening timely access to farmers to quality inputs; strong farmer–institution–industry interface; and encouraging food processing industries and greater exports.

12.13.2 Interventions

12.13.2.1 Research and Development

- To formulate market-aligned research and development programs for developing higher shelf-life varieties, increasing shelf-life through improved packaging technologies, etc.
- To improve food safety and quality standard through developing domestic standards and/or adopting global standards, strengthening food testing network, etc.

- Developing customized market information, intelligence, and forecasting system for farmers

12.13.2.2 Technologies and Practices

- Improving supply chain efficiency to avoid postharvest and transition losses
- To align production systems with market demand for mitigating the risks
- Strengthening of local market for improving the access of farmers to quality and timely inputs such as seeds, pesticides, fertilizers, credit, insurance, and information

12.14 Adaptation Priorities and Opportunities

The objectives are to outline the approach for identification of potential adaptation options for agriculture and prioritize the potential adaptation options to respond to the climate change. The whole exercise can be undertaken through a workshop in which experts with wide experience on adaptation participate. Experts may be invited from the scientific, technical, and farming communities besides policymakers and youths. The ranking and prioritization of the adaptation options are carried out using the following four steps:

- First, various potential adaptation options based on literature survey are identified and listed for the experts. Additional options are sought from the experts based on their experience and a composite list is prepared.
- Second, the experts are asked to rank (1–5 scale) those options based on the qualitative assessment of each priority. Scores are attached for each of the options and for each of the criteria, ranging from 1 to 5, indicating very low priority (1) to very high priority (5). The number of experts giving a particular rank (1–5) to each option is counted which is multiplied by 1, 2, 3, 4, and 5, respectively, to get the total score. The 10 most relevant options are short-listed based on this total score and subjected to further ranking and prioritization.
- Third, ranking of the options is done based on such characteristics as importance, urgency, no-regret, co-benefits for other domains, and mitigation effect as judged by the experts. The importance (i.e., effectiveness in avoiding damages) of an option reflects the level of necessity to implement that option in order to avoid negative impacts. These options can reduce major damages related to climate change and could generate substantial gross benefits. The urgency of the option relates to the need of implementing the adaptation option immediately or whether it is possible to defer action to a later point in time. “No-regret” options are the adaptation options for which non-climate-related benefits, such as improved air quality, will exceed the costs of implementation; hence, they will be beneficial irrespective of future climate change taking place. The criterion “co-benefit” has been specifically designed to reduce the climate change-related vulnerability while producing corollary benefits that are not related to climate change (Abramovitz et al. 2002). In the effect on mitigation, the adaptation options will also induce a reduction of greenhouse gas emissions and thus score very high on mitigation effect. The ranking is based on a weighted summation of the scores on the criteria (1) importance (weight 40 %), (2) urgency (weight 20 %), (3) no-regret characteristics (weight 15 %), (4) co-benefits (weight 15 %), and (5) mitigation effect (weight 10 %) (de Bruin et al. 2009).
- Fourth, ranking of the options is done according to the feasibility criteria. The feasibility is scored based on the technical, societal, and institutional complexities that accompany the implementation of proposed measures. The following criteria of weightaging are used: technical complexity (20 %), societal complexity (40 %), and institutional complexity (40 %) (de Bruin et al. 2009). Technical complexity refers to the technical difficulties and challenges which accompany the realization of the adaptation option, such as the technical facilities that have to be realized or mobilized; the technological uncertainties which accompany the implementation; and the uniqueness

of the operation and its risks. Social complexity involves the diversity of values which are at stake when the option will be implemented, the changes which are necessary in the perceptions of stakeholders, the necessity of their cooperation, etc. As the institutional complexity of implementing an adaptation grows, there are more adjustments of the official, bureaucratic organizations, existing procedures and arrangements necessary, and more cooperation between institutional separated domains, thus resulting in a bigger tension with existing practices and structures. Scores are attached on 1–5 scale, ranging from very low (1) to very high (5) complexities.

12.14.1 Potential Adaptation Options in Indian Agriculture

A case study from literature and consultations with the stakeholders, 27 adaptation options were identified. A brief description of these options, which potentially can reduce the vulnerability of the Indian agriculture to the effects of climate change, has been provided in Table 12.8. As the options have been taken from the literature or have been suggested by a wide range of stakeholders, they include a large variety.

Out of these 27 potential options, the 10 adaptation options having the highest priority were identified. These options were climate-ready

Table 12.8 Climate change adaptation technologies in Indian agriculture based on literature survey and stakeholder consultation

Adaptation option	Description of the option
1. Climate-ready crop varieties	Crop varieties tolerant to drought, flood, and heat, giving higher yield even under extreme climatic conditions
2. Water-saving technologies	Drip, sprinkler, and laser-aided land leveling to increase water-use efficiency
3. Changing planting date	Changing planting date (early or late sowing) to avoid heat stress during flowering and maturity of crop
4. Integrated farming system	Inclusion of crop, livestock, and fishery in farming system to sustain livelihood, particularly of poor farmers
5. Growing different crops	Growing tolerant/resistant crops to withstand the adverse impacts of climate change
6. Integrated pest management	Combining physical, chemical, and biological methods of pest management
7. Crop insurance	Incentives to farmers for covering risks of climatic extremes
8. Organic farming	Use of organic sources of nutrients, avoiding the use of chemical pesticides
9. Conservation agriculture	Zero tillage, crop rotation, residue cover of soil
10. Precision farming	Precise management of water, nutrients, and pest
11. Improved nutrient management	Site-specific demand-driven and balanced use of nutrients
12. Use of efficient microbes	Use of microbes for enhancing soil fertility and crop productivity
13. Rainwater harvesting	To reduce runoff loss and recharge groundwater
14. Waste land management	Developing wastelands through water and nutrient management for forestry, agro-forestry, grassland, and crop production
15. Improved weather-based agro-advisory	Forecasting of weather, particularly extreme agro-advisory events, for crop management planning
16. Growing crops in polyhouse	Protected cultivation of crops in polyhouse for control of temperature, moisture, pests, etc.
17. Increasing irrigation facilities	Bringing more area under irrigation through minor irrigation schemes, check dams, shallow tube wells
18. Intercropping/mixed cropping	Growing more than one crop to increase productivity and avoid crop failure
19. Creation of seed bank	To provide quality seed to poor farmers, especially useful in case of late onset of monsoon or failure of germination of first sowing
20. Intensifying crop production	Increasing crop production through intensive use of fertilizer and irrigation. This would provide enough food for the years of low production

(continued)

Table 12.8 (continued)

Adaptation option	Description of the option
21. Agro-horticulture, agro-forestry	Agro-horticulture and agro-forestry are more tolerant to drought and flood compared to food crops
22. Cooperative farming	Useful for poor farmers with small landholdings. Farmers joining together can adopt new technologies and bear more risks
23. Use of nanotechnology	To increase nutrient- and water-use efficiency
24. Use of nonconventional energy	Use of solar and wind energy to substitute fossil fuel-based conventional energy sources
25. Use of biofuel	Use of biofuel, particularly from nonedible crops and crop residues, in conjunction with fossil fuel
26. Relocating crops into alternate areas	Identifying the crops and regions that are more sensitive to climate changes/ variability and relocate them in more suitable areas
27. Indigenous technical knowledge	Harnessing indigenous technical knowledge of farmers for weather forecasting and crop management

crop varieties, water-saving technologies, changing planting dates, integrated farming system, growing different crops, integrated pest management, crop insurance, conservation agriculture, improved weather-based agro-advisory, and improved nutrient management.

12.15 Conclusions

As climate change unfolds through the early decades of the twenty-first century, adaptation will become the pivotal response to maintain food security and self-sufficiency, to retain vibrant rural communities, and to sustain globally important agricultural exports.

Much needs to be done to enable society to adapt to conditions that are already changing, and to further change, which may now be largely unavoidable. Early preparation to adapt is both sound practice and likely to confer national benefit and competitive advantage under almost any likely climatic outcome. Furthermore, it is highly likely that many of the adaptations developed in one country will have great value in helping other countries and societies to stabilize food production and to offset or avoid some of the more serious consequences of climate change. This is a role for which past contributions and current expertise equip it well to contribute solutions to this global challenge.

Adaptation alone cannot absorb all the projected impacts of climate change, especially over the long term. Some of these can be further avoided, reduced, or delayed by effective reduction in global net greenhouse gas emissions. Agriculture and forestry hold great potential for mitigating greenhouse gas emissions through afforestation, soil carbon management, and better management of livestock and cropping emissions. Making the right energy choices for the future from among our abundant resources and technologies will often be an issue of which energy source, or combination of sources, best suits a particular context. World's greatest need is for low emission technologies that are competitively priced, resilient, and flexible enough to cope with a range of possible future energy challenges and demands. All options are still in the mix for a future energy system with many niches and opportunities.

To adapt to climate change, farmers will need to broaden their crop genetic base and use new cultivars and crop varieties. They will need to adopt sustainable agronomic practices such as shift in sowing/planting dates, use of cover crop, live mulch and efficient management of irrigation, and reduce the vulnerability of soil-based agricultural production systems through the management of soil fertility, reduced tillage practices, and management of the cycle of soil organic carbon more efficiently in grasslands and cropping systems. There will be a need to monitor pathogens, vectors, and pests and assess how well natural population control is working.

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Climate Change Mitigation

13

Abstract

A variety of options exists for the mitigation of GHG emissions in agriculture. The most prominent options are improved crop and grazing land management (e.g., improved agronomic practices, nutrient use, tillage, and residue management), restoration of organic soils that are drained for crop production, and restoration of degraded lands. Lower but still significant mitigation is possible with improved water and rice management; set-asides, land-use change (e.g., conversion of cropland to grassland) and agro-forestry as well as improved livestock and manure management. Emissions from livestock production can be reduced through improved nutrition and better management of manure. In addition, crop- and pasturelands can sequester significant amounts of carbon and therefore contribute to offsetting emissions from other sources, while improving soil quality and health. Many mitigation opportunities use current technologies and can be implemented immediately, but technological development will be a key driver ensuring the efficacy of additional mitigation measures in the future. GHG emissions could also be reduced by substituting fossil fuels with energy produced from agricultural feedstocks (e.g., crop residues, dung, energy crops), which would be counted in sectors using the energy.

Overall, the outlook for GHG mitigation in agriculture suggests that there is significant potential. Current initiatives suggest that synergy between climate change policies, sustainable development, and improvement of environmental quality will likely lead the way forward to realize the mitigation potential in this sector.

Keywords

Mitigation • Cropland management • Grazing land management • Land-use change • Livestock management • Carbon sequestration • Energy management • Mitigation potential

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Climate change mitigation encompasses the actions being taken, and those that have been proposed, to limit the magnitude and/or rate of long-term global warming-induced climate change. Climate change mitigation generally involves reductions in human (anthropogenic) emissions of greenhouse gases (GHGs) and also by increasing the capacity of carbon sinks, e.g., through reforestation. Mitigation is defined as all human interventions which reduce the sources of greenhouse gases or which embrace the sinks of greenhouse gases (UNDP 2008).

There are two ways by which agricultural production can contribute to mitigate climate change that are in line with the "food security first" objective. The first way is to improve efficiency by decoupling production growth from emissions growth. This involves reducing emissions per kilogram of food output (included in this calculation are the effects of emissions from reduced deforestation per kilogram of food). The second way is to enhance soil carbon sinks. The IPCC estimates the global technical mitigation potential from agriculture could reach the equivalent of 5,500–6,000 t of CO_2 per year by 2030 (IPCC 2007b). This is grossly equivalent to three quarters of the sector's emissions in 2030 (around 8,200 t of CO_2). About 70 % of this identified potential lies in developing countries, 20 % in OECD countries, and 10 % for EIT countries. About 89 % of this potential could be achieved through soil carbon (C) sequestration. Mitigation of CH_4 can provide 9 % (through improvements in rice management and livestock/manure management), and mitigation of N_2O can provide 2 % (primarily through cropland management). IPCC estimates that nine-tenths of the global mitigation potential of agriculture is linked not to reduction of agricultural GHG (mainly CH_4 and N_2O) emissions but to managing land carbon stocks. This involves enhanced soil carbon sequestration, reduced tillage, improved grazing management, restoration of organic soils, and restoration of degraded lands.

Reducing emissions per kilogram of a given output might well be, for food security and agriculture, one of the main targets. A potential reduction equivalent to 770 t of CO_2 per year by 2030 has been identified from the reduction of fossil fuel use through improved on-farm energy efficiency (IPCC 2007b). In addition, there are potential reductions through improved efficiency in food chains, including a reduction of postharvest losses. These indirect gains include reduced emissions from deforestation (not accounted in IPCC's calculations of the 90 %) as less land is necessary to produce the same amount of food. Indirect gains also include reduced emissions from the production of fertilizer or energy inputs used on the farm.

The more we learn about greenhouse gases and climate change, the more we understand that each of us can help reduce emissions. The good news is that many practices that will help farmers achieve their goals of improved productivity such as improved livestock nutrition and reduced water use also reduce GHG emissions.

Agriculture is well-positioned to make a difference. Properly managed, healthy soils may act as a "sink" to remove GHG emissions from the atmosphere. Natural areas found on many farm properties such as wetlands, woodlots, pastures, and buffers can also trap GHGs. Increasingly there are viable opportunities for on-farm green energy generation, such as the production of biogas. Agricultural operations can participate in reducing atmospheric GHGs by adopting processes or activities that:

- Reduce the amount of GHGs released into the atmosphere (GHG sources)
- Remove GHGs from the atmosphere by storing them in soils (e.g., by growing perennial tallgrass crops) or removing them (GHG sinks)

The magnitude of the challenge to stabilize GHG concentrations in the atmosphere and limit average temperature increases makes it imperative that the contributions of all sectors with significant mitigation potential be tapped to the fullest extent possible. Agriculture is recognized as a sector with such potential, and farmers, ranchers, herders, and other land users around the world can and should be part of the solution to climate change.

In the IPCC's fourth assessment report, Smith et al. (2007) distinguish seven broad sets of options for mitigating GHG emissions from agricultural ecosystems:

- *Cropland management*, including nutrient management, tillage and residue management (irrigation, drainage), rice paddy management, agro-forestry, set-asides, crop rotations, and land-use change
- *Grazing land management and pasture improvement*, including grazing intensity, increased productivity (e.g., fertilization), nutrient management, fire management, and species introduction (including legumes)
- *Management of organic soils*, including avoiding drainage of wetlands
- *Restoration of degraded lands*, including erosion control, organic amendments, and nutrient amendments
- *Livestock management*, including improved feeding practices, dietary additives, longer-term structural and management changes, and animal breeding
- *Manure management*, including improved storage and handling, anaerobic digestion, and more efficient use as a nutrient source
- *Bioenergy*, including energy crops (solid, liquid, biogas, and residues)

Land management options for mitigation fall in the following categories:

13.1. **Cropland management**
    13.1.1. Agronomy
    13.1.2. Nutrient management
    13.1.3. Tillage/residue management
    13.1.4. Water management
    13.1.5. Rice management
    13.1.6. Manure management
    13.1.7. Agro-forestry
    13.1.8. Land-use change
    13.1.9. Restoration of degraded lands
    13.1.10. Organic agriculture
13.2. **Livestock management**
    13.2.1. Feed optimization
    13.2.2. Genetically modified rumen bacteria
    13.2.3. Straw ammonization and silage
    13.2.4. Grazing land management
    13.2.5. Longer-term management changes and animal breeding
13.3. **Energy management**
    13.3.1. Agriculture for biofuel production

13.1 Cropland Management

Often intensively managed croplands offer many opportunities to impose practices that reduce net GHG emissions (IPCC 2007a). These opportunities are diverse and are often grouped in terms such as conservation agriculture, sustainable agriculture, etc. Essentially, these categories aim to minimize soil disturbance while maximizing yield. Land management practices for mitigation regarding croplands include the following partly overlapping categories:

13.1. **Cropland management**
    13.1.1. **Agronomy** (using improved crop varieties, extending crop rotations, avoiding or reducing the use of bare fallow and the use of rotations with legume crops)
        13.1.1.1. Using improved crop varieties
        13.1.1.2. Cover crop technology
    13.1.2. **Nutrient management** (practices that improve nitrogen use efficiency-precision farming (i.e., adjusting application rates of nutrients based on precise estimation of crop needs); using slow- or controlled-release fertilizer forms or nitrification inhibitors (which slow the microbial processes leading to N_2O formation); improved timing of nitrogen application, often just prior to plant uptake; placing the nitrogen more precisely to make it more accessible to crops roots; or avoiding nitrogen applications in excess of immediate plant requirements)
        13.1.2.1. Nitrogenous fertilizers
        13.1.2.2. Mycorrhiza
    13.1.3. **Tillage/residue management** (minimal tillage or no-tillage systems, crop residue management, avoiding the burning of crop residues)
        13.1.3.1. Conservation tillage
        13.1.3.2. Biochar

        - 13.1.3.3. Off-field crop residue management
    - 13.1.4. **Water management** (expanding the use of irrigation or using more effective irrigation measures, cropland drainage in humid regions)
        - 13.1.4.1. Irrigation
            1. Drip irrigation
            2. Sprinkler irrigation
        - 13.1.4.2. Fog harvesting
        - 13.1.4.3. Rainwater harvesting
    - 13.1.5. **Rice management**
        - 13.1.5.1. Fertilizer, manure, and straw management
        - 13.1.5.2. Mid-season drainage
        - 13.1.5.3. Alternate wetting and drying
        - 13.1.5.4. Potassium fertilizer application
        - 13.1.5.5. Agricultural biotechnology
        - 13.1.5.6. Reduced tillage
        - 13.1.5.7. Direct seeding
        - 13.1.5.8. Chemical fertilizer amendment
        - 13.1.5.9. Electron acceptors
    - 13.1.6. **Manure management**
        - 13.1.6.1. Covering manure storage facilities
    - 13.1.7. **Agro-forestry (mitigation)**
    - 13.1.8. **Land-use change**
    - 13.1.9. **Restoration of degraded lands**
    - 13.1.10. **Organic agriculture**

13.1.1 Agronomy

Increased soil carbon storage can be achieved through improved agronomic practices. These practices increase yields while also generating higher inputs of carbon residue. Examples of agronomic practices are using improved crop varieties, extending crop rotations, and avoiding or reducing the use of bare fallow. Adding additional nutrients through fertilizers can also promote soil carbon gains. However, the benefits of increased soil carbon can be (partly) offset by higher N_2O emissions from the soil and higher CO_2 emissions from the manufacturing of the fertilizer.

Moreover, emissions from the land can also be reduced through the adoption of systems that have a reduced reliance on fertilizers, pesticides, and other inputs. Not only does this prevent the greenhouse gas emissions from the manufacturing of these inputs, it also increases soil carbon. An important example is the use of rotations with legume crops. These crops reduce reliance on external nitrogen inputs, which reduces the demand for fertilizer.

Another group of agronomic practices are those that provide temporary vegetative cover between successive agricultural crops or between rows of tree or vine crops. These “catch” or “cover” crops add carbon to soils and may also extract plant available N unused by the preceding crop, thereby reducing N_2O emissions.

13.1.1.1 Crop Varieties with Enhanced Carbon Sequestration

Agricultural biotechnology stands out as a promising tool for the development of traits and varieties that help to mitigate and adapt to climate change. GM crops with pest resistance (Bt) and herbicide tolerance and conventionally bred varieties using marker selection in tissue culture have benefited agriculture by improving productivity and disease resistance. Had productivity not been maintained or increased by such GM crops, more land would have to be cultivated, and it is likely that such land would come from the forest or other more natural ecosystems with sequestered carbon that would be released when tilled for growing crops. There are three ways that a GM crop can reduce GHG emissions: (1) increasing the productivity and the amount of residue carbon that can be sequestered, (2) herbicide-resistant crops enable greater use of no-till which helps preserve carbon sequestration, and (3) because of enabled no-till, the amount of fossil fuel used by tractors and other implements is reduced because no-till involves fewer passes of equipment across the field.

Crop varieties that have been created by traditional plant selection methods have no barriers to dissemination, and they are accepted worldwide. On the other hand, plant varieties resulting from GM crops have faced stiff opposition from consumers in several parts of the world, most notably in Europe. Moreover, the resultant seeds are often relatively expensive so they may not be available to the poorest farmers.

(i) *Advantages*
  - A big advantage of biotechnology is that, besides increasing carbon sequestration, it can help to improve the productivity of crop plants.
  - By selecting cultivars that are more responsive to elevated CO_2 and more resistant to heat stress, crops will be better adapted to future climatic conditions.

(ii) *Disadvantages*
  - The method generally requires several years and generations of plants to implement because yield and carbon sequestration are dependent on many abiotic and biotic factors. The pace of variety development may be slower than changes in atmospheric CO_2 and climate.
  - Whole new research programs are needed for identifying varieties and traits responsive to the increases in atmospheric CO_2 and global warming and their interactions on the productivity, grain quality, water relations, and pest resistance of crops, and such research is expensive (Ainsworth et al. 2008).
  - To be successful, selection needs germplasm that differs in many traits, and there may not be enough range in variation of crucial traits needed to adapt to climate change.
  - Many varietal crosses require the use of growth chambers or greenhouses with potted plants, which makes it difficult to predict responses under field conditions.

Traditional plant selection is used worldwide to improve plant varieties, often with the aim of matching them to local growing conditions. Newer biotechnology requires specialized equipment and laboratories as well as more trained personnel; therefore, it tends to be a technology that is confined to more developed countries. Because of the high cost of facilities that can produce conditions with elevated CO_2 and temperature as expected with global change, relatively few field experiments have been conducted (Ainsworth et al. 2008), and they have tended to be in developed countries, with China and India as exceptions. Approximately 250 million acres of biotechnology-engineered maize, canola, cotton, soybeans, papaya, sugar beets, sweet corn, and squash crops have increased global farmer profits by about US$27 billion, reduced pesticides application by 224 million kg, reduced environmental impacts of pesticides by 14 %, and reduced GHG emissions by 960 million kg of CO_2 (Brookes and Barfoot 2009). On the basis of the above advantages of GM crops, several companies such as Monsanto, Syngenta, and DuPont Pioneer have started to use these germplasm in their research and development pipelines.

Varieties with increased yield for whatever reason improve the profitability of farmers. Many commercial seed companies are hugely successful. Therefore, the economics of using improved varieties, whether by traditional plant selection or by biotechnology, have been very positive, and it is very likely that they will continue to be positive with future climate change. As mentioned above, besides benefiting agriculture by improving productivity and disease resistance, improved plant varieties have decreased GHG emissions by reducing demand for cultivated land and fossil fuel-based inputs. GM crops conserve over 14,200 million kg of CO_2 – the equivalent of removing over six million cars from circulation in 2007 alone (Brookes and Barfoot 2009).

13.1.1.2 Cover Crop Technology

Cover cropping is an effective method of reducing emissions of CO_2. These crops grow over entire land areas or in localized spots such as grassed waterways, field margins, and shelterbelts. Compared to leaving fields fallow, they reduce emissions and can sequester carbon during periods when primary crops are not grown. Cover crops are usually an option on surplus agricultural land or on cropland of marginal productivity.

Cover crops are fast-growing crops such as winter rye and clovers that are planted between periods of regular crop cultivation. By covering the soil surface, they protect the soil from erosion, and if leguminous, they fix nitrogen. Later, when plowed under, they provide humus and carbon to the soil as well as nitrogen for the subsequent crop.

Adoption of cover crops is limited because of the many concerns of growers and the specificity of profitable cropping systems. Lack of knowledge, incorrect choice of cover crop, and the economic costs of planting and terminating cover crops are all concerns of growers, and they have led to the slow adoption of this practice. If land is fallow for portions of the year, cover crops should be considered. However, they need to be selected on the basis of the growing season, protection capacity, nitrogen-fixing capability, and economic feasibility. They vary from region to region, cropping system to cropping system, and crop season to crop season. Therefore, local research must be conducted in order to obtain the knowledge needed to use this practice reliably.

(i) *Advantages*
  - A primary advantage is that by increasing plant residues and roots, cover crops can sequester carbon during times when the soil surface would normally be bare and emitting carbon due to soil respiration.
  - Cover crops can alleviate nutrient deficiencies and reduce artificial fertilizer use by nitrogen fixing, if leguminous. This will save fossil fuel used in fertilizer manufacture, although more nitrogen in the soil can increase N_2O emissions.
  - Cover crops reduce soil erosion as well as rainfall runoff by improving water infiltration and water adsorption in the soil matrix.
  - Cover crops can also reduce use of pesticides and herbicides for the associated cash crop by suppressing weed growth and providing a substantial habitat for beneficial arthropods.

(ii) *Disadvantages*
  - There are costs associated with planting and terminating cover crops.
  - If not terminated properly, cover crops may act like weeds and compete with the following cash crops for light, nutrients, and water.
  - The residues from cover crops can potentially interfere with postemergence herbicides, which results in the escape of weeds.
  - In some cases, the additional water requirement of the cover crops may make this practice economically and environmentally less viable.

Several examples have been presented showing that the growing of cover crops is profitable. In one experiment hairy vetch was grown during the off-season for a main crop of corn. The costs of fertilizer and of hairy vetch seed required for the no-till zero-tillage cover crop systems were \$117.08 and \$16.62 ha^{-1} year^{-1}, respectively, while the cost of fertilizer for conventional no-tillage system was \$174.97 ha^{-1} year^{-1}. The cover crop system produced average corn yield of 7.86 Mt ha^{-1} in a no-tillage conventional system. The average gross margin (profit) was \$238.28 ha^{-1} year^{-1} in cover crop system and \$233.27 ha^{-1} year^{-1} in conventional no-tillage system.

Cover crops can also increase soil carbon sequestration. Lal (1998) lists carbon sequestration rates from 0.28 to 2.60 Mg ha^{-1} year^{-1} from growing cover crops on an eroded Alfisol in Western Nigeria.

13.1.2 Nutrient Management

Plant nutrient management to increase soil nutrients and thus enhance crop productivity is a major technological challenge for ensuring food security and sustaining rural development. Plant nutrition management is essential to sustain and enhance crop productivity to meet the demand for food and raw materials and to maintain the quality of land and water resources. To ensure soil health, accurate inventorization of soil resources is a prerequisite. Soil health can be improved through several site- and soil-specific management options. The application of integrated nutrient management techniques has been found to increase nutrient use efficiency by integrating and balancing the nutrient dose in relation to nutrient status and crop requirements.

Improving nutrient use efficiency can reduce N_2O emissions and indirectly reduce greenhouse gas emissions from fertilizer manufacturing (IPCC 2007c). This is due to the fact that nitrogen applied in fertilizers, manures, and biosolids is not always used efficiently by crops, and the remaining nitrogen is susceptible to emission of N_2O. Improving nutrient use efficiency can also prevent off-site N_2O emissions. This is due to the reduction in nitrogen leaching and volatile losses. Examples of practices that improve nitrogen use efficiency are precision farming (i.e., adjusting application rates of nutrients based on precise estimation of crop needs); using slow- or controlled-release fertilizer forms or nitrification inhibitors (which slow the microbial processes leading to N_2O formation); improved timing of nitrogen application, often just prior to plant uptake; placing the nitrogen more precisely to make it more accessible to crops roots; or avoiding nitrogen applications in excess of immediate plant requirements.

13.1.2.1 Nitrogenous Fertilizers

Efficient use of nitrogenous fertilizers can reduce N_2O emissions from agricultural fields. In addition, by reducing the quantity of synthetic fertilizers required, improved management can also reduce CO_2 emissions associated with their manufacture. A variety of fertilizer management technologies are discussed in brief, followed by a discussion on their relative advantages and disadvantages.

(i) *Nitrous oxide mitigation in organic agriculture*: Organic agriculture reduces emission of N_2O due to the ban on the use of mineral nitrogen. A diversified crop rotation with green manure in organic farming improves soil structure and diminishes emissions of N_2O, although the nitrogen provided by the green manure does contribute to N_2O emissions. Soils in organic farming are more aerated and have significantly lower mobile nitrogen concentrations, which reduces emissions of N_2O. Since organic crop systems are limited by the availability of N, they aim to balance their N inputs and outputs and their N use efficiency. Thus, their emissions are lower than those of conventional farming systems per unit of land area. However, with lower yields from organic farming, the emissions per unit of produce could be the same or higher (Petersen et al. 2006).

(ii) *Mitigation using nitrification inhibitors*: Emission of N_2O can be reduced by using nitrification inhibitors which slow the microbial processes that lead to N_2O formation (Fig. 13.1) (Robertson 2004). The use of nitrification inhibitors such as sodium benzylisothiouronium butanoate (SBT butanoate) and sodium benzylisothiouronium fluroate (SBT fluroate) increased yield of crop plants (Table 13.1), reduced emissions of N_2O by 4–5 %, and, because N_2O is a more potent greenhouse gas than CO_2, reduced global warming potential by 8.9–19.5 % compared to urea treatment alone, thereby helping to mitigate N_2O emission (Bhatia et al. 2010).

Nitrification and urease inhibitors can reduce the loss of N as N_2O. The application of dicyandiamide (DCD) and nitrapyrin to grassland reduced the emission of N_2O from NH_4^+-based fertilizers by 64 % and 52 %, respectively (McTaggart et al. 1994).

(iii) *Slow-release fertilizer application and manipulation technologies*: Fertilizer application technology significantly influences

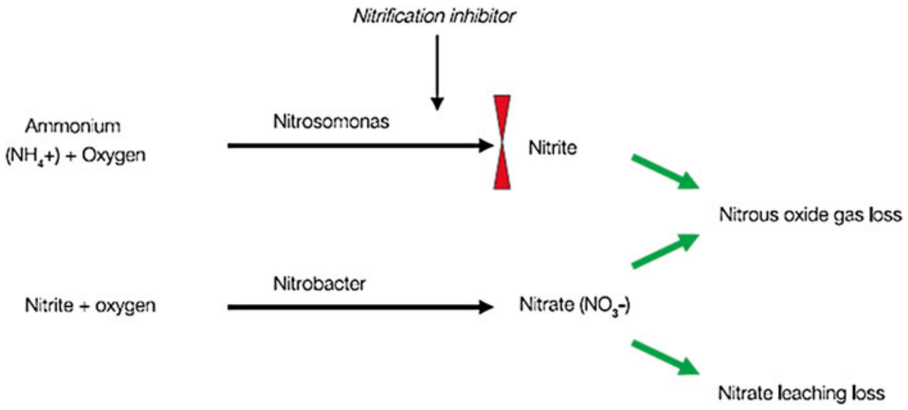

Fig. 13.1 Nitrification inhibitors (e.g., dicyandiamide) reduce the activity of nitrifying bacteria

Table 13.1 Summary of corn yield responses from nitrification inhibitors added to ammoniacal fertilizers applied at varying times in several regions of the USA (Nelson and Huber 2001)

Region	Time of application	% of studies with yield increase	% yield increase
Southeast (GA, MD, NC, SC, TN)	Autumn	17	14
	Spring	43	15
Eastern Corn Belt (IL, IN, OH, KY)	Autumn	69	9
	Spring	51	3
	Spring (no-till)	82	13
Northern Corn Belt (MI, MN, WI) Not irrigated	Autumn	25	5
	Spring	17	12
Western Corn Belt (KS, MN, NE) irrigated coarse-textured soils	Spring	52	30
Western Corn Belt (KS, NE) Medium- and fine-textured soils	Spring	10	5

nitrous oxide emissions. The various parameters of this technology are described below:

- The use of slow-release fertilizers offers a cost-effective mitigation option. Slow release of urea- and NH$_4$-based fertilizers can be achieved by using various coatings, chemical modifications, and changing the size of fertilizer granules. For example, increasing the size of urea granules from conventional 0.01 to 1 g decreased nitrification rates and was shown to be more effective than adding the nitrification inhibitor DCD (Skiba et al. 1997).
- A combination of increasing the size of pellet to 1 g and adding DCD led to very slow nitrification rates, with 30 % of the original N application still present 8 weeks after fertilizer application (Goose and Johnson 1993).
- Global warming potential (GWP) due to N$_2$O reduced from 231 kg CO$_2$e ha^{-1} on urea application to 200 kg CO$_2$e ha^{-1} under urea and SBT fluroate treatment under conventional tillage, whereas under zero-tillage it was reduced from 260 kg CO$_2$e ha^{-1} with urea alone to 210 kg CO$_2$e ha^{-1} with SBT fluroate (Bhatia et al. 2010). These reductions in global warming potential were 13.5 % and 19.5 % due to SBT fluroate compared to urea alone under conventional and zero-tillage, respectively.

(iv) *Nitrogen management technology*: Fertilizer nitrogen management practices significantly influence the emissions of

N_2O in agriculture. These practices are fertilizer type, timing, placement, and rate of fertilizer application, as well as coordinating the time of application with irrigation and rainfall events. Each direct nitrogen management practice influences nitrous oxide emissions.

(a) *Type of fertilizer:* Nitrous oxide production can be affected by the form of fertilizer applied. Venterea et al. (2005) observed that plots amended with anhydrous ammonia emit N_2O at rates 2–4 times greater than from those amended with urea, ammonium nitrate, or broadcast urea. Tenuta and Beauchamp (2003) found that the relative magnitude of total emissions was greater from urea than from ammonium sulfate, which in turn was greater than that from calcium ammonium nitrate. The nitrate-based fertilizer resulted in significantly lower emissions of N_2O than ammonium-based fertilizer. Snyder et al. (2007) demonstrated that slow, control release and stabilized N fertilizer can enhance crop productivity and minimize the N_2O emissions. Emissions of N_2O were significantly higher from a soil fertilized with urea compared to NH_4NO_3 (McTaggart et al. 1994). NH_4NO_3 was beneficial in reducing the volatilization of NH_3 and the emission of N_2O. Another compound, NH_4HCO_3, when used as basal fertilizer, contributed less to N_2O in contrast to urea.

(b) *Fertilizer N timing*: Synchronous timing of N fertilizer application with N demand from plants is an important factor in determining the emissions of N_2O from row crop cultivation. Crop nitrogen intake capacity is generally low at the beginning of the growing season, increasing rapidly during vegetative growth, and dropping sharply as the crop nears maturity. Prior to spring crop planting results in increased soil N with poor plant N uptake, and therefore, it results in increased N_2O emissions. About 30 % of the US area cropped to corn is fertilized in autumn (CAST 2004). Therefore, large emissions of N_2O could potentially be avoided by fertilizing in spring rather than autumn. Hultgreen and Leduc (2003) showed that emissions of N_2O were lower following spring N fertilizer application compared to autumn application.

(c) *Fertilizer N placement*: Placement of N fertilizer into the soil near the zone of active root uptake may reduce surface N loss and increase plant N use resulting in a reduction in N_2O emissions (CAST 2004). Liu et al. (2006) found that injection of liquid urea ammonium nitrate at a deeper level in soil profile (10–15 cm) resulted in 40–70 % lower emission of N_2O compared to shallow injection (5 cm) or surface application. Hultgreen and Leduc (2003) reported that the N_2O emissions were reduced when urea was broadcast in mid-row rather than side-banded.

(d) *Fertilizer N rate*: The emission of N_2O correlates well with fertilizer N rate (Drury et al. 2008). Millar et al. (2010) also report that increasing the amount of N applied to soil resulted in increasing emissions of N_2O.

Global warming potential in a no-N treatment of conventional transplanted rice was 1,419 kg CO_2e ha^{-1}, whereas GWP under traditional nutrient application of NPK was 6,730 kg CO_2e ha^{-1} (Pathak 2010). The loss in yield was not significant.

Millar et al. (2010) suggested that the incentive for N_2O emission reduction by application of lower nitrogen application rates within a profitable range ultimately could be financially remunerated through a carbon or nutrient market. That would bring economic and environmental advantages to compensate for lost productivity benefits due to the use of higher nitrogen application rates.

(e) *Coordination with irrigation and rainfall events*: Application of fertilizer immediately after rain will increase N use efficiency of plants and mitigate N_2O emissions. Losses of nitrogen through leaching, volatilization, and denitrification in a farmer's rice field (which had received 67.5 kg N ha^{-1} after rain) decreased up to 40.5 kg N ha^{-1} compared to total amount of loss which was 80.3 kg N ha^{-1} with the farmer's practice of alternate flooding. The exception was when there were mid-season drainage or alternate flooding and drainage cycles, in which case it increased (Pathak 2010). The N management regime also reduced global warming potential (GWP) by 1–9 %.

Nitrogen fertilization is a significant input cost for farmers worldwide, and therefore, some of the approaches, such as split applications of fertilizer to better match plant uptake needs, are in common use. On the other hand, chemical inhibitors are relatively expensive, so they are less widely used, but nevertheless have gained some acceptance as suggested by the number of positive yield studies in the USA.

(v) *Advantages*

- Reductions in N_2O emissions can be achieved by relatively simple adjustments in the farming practices, such as using fertilizer in larger granules and applying it in more frequent, smaller applications, yet high productivity can be maintained.
- Increase in farm N use efficiency will reduce leaching of NO_3^- to groundwater.
- Making crops more N use efficient will decrease the need for inorganic N fertilizers and thereby reduce emissions from fossil fuel associated with their manufacture.

(vi) *Disadvantages*

- The use of chemical inhibitors of N_2O emissions may leave unacceptable residues, and they may not be effective in certain types of soil.
- The present prices of chemical inhibitors of N_2O emission are quite high, so they are not affordable to many farmers, and they are not commercially available in many regions.

(vii) *Interventions*

(a) *Research and development*

- Enhancing the understanding of soil nutrient dynamics, crop nutrient requirements, and nutrient transformations in soil to increase nutrient use efficiency and to improve the stock of plant nutrients in the soil
- Economic evaluation of each integrated nutrient management technology and identification of constraints in the adoption of each technology

(b) *Technologies and practices*

- Promotion of organic farming to improve the land quality and reduce carbon footprint
- Improving management of inorganic fertilizers through proper timing of fertilizer application, use of innovative fertilizer material, and development of soil testing techniques
- Developing cultures of microorganisms and techniques which hasten the process of composting for producing good quality compost
- Promoting efficient management of crop residues in rice–wheat system
- Promoting recycling of crop/farm wastes and their conversion into easily transportable and usable forms for effective utilization in plant nutrient supply
- Planning the sequencing of crops based on their nutrient demands, nutrient uptake efficiencies, and residues
- Breeding and selection of superior N-fixing legume species and cultivars, short duration pulses, and fast-growing fodder legumes for green manuring

- Management of mycorrhiza and other promising beneficial microorganisms
- Focusing efforts towards correcting micronutrient deficiencies
- Using nitrification inhibitors to reduce chemical use and promote INM
- Integration of agro-forestry with cropland management to increase sequestration of soil carbon and reduce nutrient leakage
- Quality labeling and specifying microorganism application for agriculture, horticulture, greenhouse products, etc.

13.1.2.2 Mycorrhiza

Mycorrhiza assists plants in obtaining soil nutrients. Therefore, any resulting stimulations in plant growth provide additional plant residue, which in turn can lead to increased carbon storage in the soil (Smith et al. 2008). However, mycorrhiza can also promote carbon sequestration through a second mechanism. Mycorrhizae release glomalin, which is a glycoprotein that serves as gluing agent that facilitates soil aggregate formation, improvement of soil physical properties, and sequestration of carbon in the soil (Rillig 2004; Subramanian et al. 2009). The stability of soil aggregates is highly correlated with the length of mycorrhizal hypha in the soil (Jastrow et al. 1998).

One of the prime factors associated with enhancing soil carbon sequestration is the release of glomalin in mycorrhizal systems. Specific mycorrhizae, *Glomus intraradices*, *G. mosseae*, *G. fascicullatum*, *G. margarita*, and *G. pellucida*, have been reported to enhance soil carbon due to the release of glomalin. Glomalin is a glycoprotein that serves as gluing agent that facilitates soil aggregate formation and improves soil physical properties (Rillig 2004). Glomalin secretion helps to conserve soil carbon besides increasing microbial biomass. Subramanian et al. (2009) reported that glomalin is composed of 45 % carbon, like most organic compounds, and it is considered to be a major compound that is a store of carbon in soil carbon sequestration. Since glomalin is a reservoir of carbon, examining it helps explain amounts of C sequestration in a maize-mycorrhizal system. Arbuscular mycorrhizal fungi (AMF) release glomalin which stores about 30–40 % carbon in the form of carbohydrates and proteins. It is a superglue that helps store carbon, nutrients, and beneficial microorganisms, as well as being involved in stabilizing soil aggregates. It also offers protection against biotic and abiotic stress conditions that could decrease crop growth and therefore reduce carbon sequestration (Subramanian et al. 2009).

Mycorrhizal inoculation resulted in colonization of roots irrespective of fertility gradients and crop growth stages (Subramanian et al. 2009). The uninoculated treatments registered less than 5 % colonization shortly after planting, but the percentage of colonization tended to increase significantly with the advancement of plant growth. The glomalin content of the soil substantially increased with mycorrhizal association, suggesting that mycorrhiza plays a vital role in conserving the carbon in a long-lived pool, which prevents loss of carbon to the atmosphere while sustaining soil fertility. Although soil glomalin concentration was not affected by chemical fertilizer levels, combined application of fertilizer and rice straw significantly increased soil glomalin concentration, which result into the greater soil organic carbon conservation (Subramanian et al. 2009).

Mycorrhizal plants are generally photosynthetically more active and capable of converting more atmospheric CO_2 into assimilates in the plants (Subramanian et al. 2009). Mycorrhizal symbiosis utilizes at least 10 % of the host plant's photosynthetic carbon which helps the microbial activity in the rhizosphere and contributes to the enhancement of active carbon pool in the soil. Shoot and root biomass of *Glomus intraradices* mycorrhiza-inoculated maize plants were significantly increased about 29 % in comparison with uninoculated plants with there being more enhancement when soil zinc levels were low (Subramanian et al. 2009). Thus, AMF that form symbiotic relationship with more than 90 % of terrestrial plant species are helpful in storing carbon in living soil pools. However, the degree of dependence on mycorrhizae varies with plant species, particularly root morphology, as well as soil and climate (Muchovej 2001). Crops with thick roots, poorly branched, and with few root hairs are more dependent on mycorrhizae including onions, grapes, citrus, cassava, coffee, and tropical legumes.

In many parts of the world, phosphate fertilizers are relatively inexpensive, and therefore farmers do not have a great incentive to inoculate with mycorrhizae. Where phosphate fertilizers are relatively expensive or unavailable, the lack of commercial inoculums and the difficulty of culturing one's own are significant barriers, although commercial sources are becoming available.

Inoculation with ectomycorrhizae is common in the forest industry, but the necessity for more difficult to produce arbuscular mycorrhizae has slowed penetration into agriculture. Nevertheless, practical applications include transplant media that have been treated to remove soil pathogens, revegetation of eroded or mined areas, and in arid and semiarid regions (Muchovej 2001).

(i) *Advantages*
  - Mycorrhizal-inoculated plants produce larger biomass as a direct consequence of improved photosynthetic activities, and they can translocate 20–30 % of assimilated carbon to the rhizosphere (underground).
  - Glomalin concentrations in the soil can be significantly enhanced by the mycorrhizal inoculation resulting in more durable soil carbon sequestration, as well as more stable soil aggregates with improved soil physical properties.

(ii) *Disadvantages*
  - Indigenous mycorrhizal fungal inoculation is not very effective and causes inhibitory effects when inorganic fertilizer is applied to the soil without any integration of organic manures.
  - Cultures of arbuscular mycorrhizae for inoculation of agricultural crops require a host plant and therefore are difficult to grow. However, they are beginning to become commercially available, at least in the USA (Muchovej 2001).

13.1.3 Tillage/Residue Management

No-tillage systems can reduce greenhouse gas emissions in a variety of ways. The same is true for minimal tillage (also called reduced tillage) systems but to a lesser extent. While previously tillage was an essential feature of farming, advances in weed control methods and farm machinery now allow many crops to be grown with minimal or no-tillage. These practices are now increasingly used throughout the world (Cerri et al. 2004).

Soil disturbances tend to stimulate soil carbon loss through enhanced decomposition and erosion. Therefore, reducing soil disturbances through minimal tillage or no-tillage systems reduces soil carbon losses. In addition, no-tillage or minimal tillage systems may affect N_2O emissions. However, the net effects on N_2O emissions are not yet well-quantified (IPCC 2007c). The effect of reduced tillage on N_2O emissions may depend on soil and climatic conditions. In some areas, reduced tillage promotes N_2O emissions, while elsewhere it may reduce emissions or have no measurable influence (Marland et al. 2001). No-tillage systems can also reduce greenhouse gas emissions from energy use.

Residue management in the form of the retainment of crop residues also tends to increase soil carbon storage. Increased soil carbon storage occurs as the residue is the precursor for soil organic matter, which is the main carbon store in the soil. Moreover, avoiding the burning of residues also avoids emissions.

13.1.3.1 Conservation Tillage

Conventional tillage is the traditional method of farming in which soil is prepared for planting by completely inverting it with a tractor-pulled plow, followed by subsequent additional tillage to smooth the soil surface for crop cultivation. In contrast, conservation tillage is a tillage system that conserves soil, water, and energy resources through the reduction of tillage intensity and retention of crop residues. Conservation tillage involves the planting, growing, and harvesting of crops with limited disturbance to the soil surface.

Fig. 13.2 Soybean in a zero-till farming system

Tillage of the soil stimulates microbial decomposition of soil organic matter, which results in emissions of CO_2 to the atmosphere. Therefore, minimizing the amount of tillage promotes sequestration of carbon in the soil. In the last decades, advancements in weed control methods and farm machinery now allow many crops to be grown with minimum tillage (Smith et al. 2008).

Conservation tillage is any method of soil cultivation that leaves the previous year's crop residue (such as cornstalks or wheat stubble) on fields before and after planting the next crop to reduce soil erosion and runoff, as well as other benefits such as carbon sequestration (MDA 2011). With this technique, at least 30 % of the soil surface is covered with crop residue/organic residue following planting (Dinnes 2004). It also features non-inversion of the soil. This type of soil tillage is characterized by tillage depth and the percentage of surface area disturbed. For example, to plant the crop in Fig. 13.2, the planter was adjusted to place the seed 50 mm deep and provide a layer of fine tilth 18 mm deep across the planted row areas in order to incorporate Treflan, which was sprayed in front of the machine. This was all completed at 20 km/h.

Conservation tillage methods include zero-till, strip-till, ridge-till, and mulch-till.

(i) *Zero-tillage*: Zero-tillage is the extreme form of conservation tillage resulting in minimal disturbance to the soil surface. Zero-till involves planting crops directly into residue that has not been tilled at all (MDA 2011). Zero-tillage technology is generally used in large-scale agricultural crop cultivation systems because large machines are required for planting (Fig. 13.2). For smaller-scale farms, no adequate machines are available for sowing, although very small-scale farmers may do so by hand. In zero-tillage, crops are planted with minimum disturbance to the soil by planting the seeds in an unplowed field with no other land preparation. A typical zero-tillage machine is a heavy implement that can sow seed in slits 2–3 cm wide and 4–7 cm deep and also apply fertilizer in one operation (CIMMYT 2010). The machine contains an inverted T-type furrow opener to open the slits (Fig. 13.3). The seed and fertilizer are placed in corresponding boxes and dropped into the slits automatically. The depth of the slits may be controlled by a hydraulic mechanism from the tractor.

Fig. 13.3 Photograph showing zero-tillage sowing implement

(ii) *Feasibility of technology and operational necessities*: Features of zero-tillage include:
  - Crop residues are distributed evenly and left on the soil surface.
  - No implements are used to turn the soil over, to cultivate the crops, or to incorporate the crop residues into the soil.
  - Weeds and cover crops are controlled by a preplanting application of non-pollutant desiccant herbicides.

A specialized planter is used to cut crop residues on the soil surface and insert the seeds and fertilizers into the soil with minimum disturbance. Generally seed sowing is done when soil moisture content is adequate for seed germination but not so high that the large tractor and planter would compact the soil.

- Weed control is also accomplished with pre- and postemergence herbicides.
- Crop rotation is fundamental to zero-tillage because it helps to minimize weed, insect, and disease populations that increase when the same crop is grown year after year on the same ground.
- Most experiments with zero-tillage have had increased yields, but in the wetter areas, it took many years to see the crop yields stabilize or increase. However, in drier areas where moisture is the major limiting factor, the effects on yield were seen even in the first year (Kimble et al. 2007).
- Zero-tillage causes stratification of soil organic carbon content with relatively higher concentration in the surface and lower in the subsoil compared to plow-based methods of seedbed preparation. The ratio of soil organic carbon content for zero-tillage to plow-till system remains.

(iii) *Strip-tillage*: Strip-tillage involves tilling the soil only in narrow strips with the rest of the field left untilled (strip-till) (MDA 2011).

(iv) *Ridge-tillage*: Ridge-till involves planting seeds in the valleys between carefully molded ridges of soil (Fig. 13.4). The previous crop's residue is cleared off ridgetops into adjacent furrows to make way for the new crop being planted on ridges. Maintaining the ridges is essential and requires modified or specialized equipment (MDA 2011).

(v) *Mulch-tillage*: Mulch-till (Fig. 13.5) is another reduced tillage system in which residue is partially incorporated using chisels, sweeps, field cultivators, or similar farming implements that leaves at least one-third of the soil surface covered with crop residue (MDA 2011).

Each conservation tillage method requires its own type of specialized or modified equipment and adaptations in management.

(vi) *Advantages*
  - Increases the ability of soil to store or sequester carbon while simultaneously enriching the soil.
  - Improves soil water infiltration, thereby reducing erosion and water and nitrate runoff.
  - Improves the stabilization of soil surface to wind erosion and the release of dust and other airborne particulates.
  - Reduces leaching of nutrients due to greater amounts of soil organic matter to provide binding sites.
  - Decreases evaporation and increases soil moisture retention, which can increase yields in drought years (Suddick et al. 2010).
  - Reduces the number of passages of equipment across the field, thereby

Fig. 13.4 Ridge-till farming system

Fig. 13.5 Mulch-till farming system

reducing the cost of fossil fuel and the associated carbon emissions to the atmosphere.

- Reduces the loss of pesticides and other applied chemicals. This is because higher infiltration rates with more surface residue results in less runoff moisture-holding capacity due to higher soil organic matter that results in less leaching.

(vii) *Disadvantages*

- Adoption of reduced tillage in humid, cool soils would primarily affect the distribution of SOC in the profile, unless carbon inputs were increased (Lal et al. 1998b).
- Specialized, expensive equipment is required or much hand labor in the case of very small-scale growers.

- Requires more herbicides and pesticides than standard conventional practices to control weeds and other pests.
- Due to the large size of the original soil carbon pools, the contribution of conservation tillage can appear to be small, and a significant amount of time is required to detect changes.
- Sizable amounts of non-CO_2 greenhouse gases (N_2O and CH_4) can be emitted under conservation tillage compared to the amount of carbon stored, so that the benefits of conservation tillage in storing carbon can be outweighed by disadvantages from other GHG emissions.

According to Brown (2008), zero-till is widely used in five countries in particular: 15 million hectares in the USA, 24 million hectares in Brazil, 18 million hectares in Argentina, and 13 million hectares in Canada. Australia has 9 million hectares under zero-till, making a total of 79 million hectares for these five countries with the most hectarage. Worldwide, the use of zero-till is increasing. In 1999, it was used on 45 million hectares, and by 2005 it had more than doubled to reach 95 million hectares. Using the latter figures, all the other countries than those in the top five accounted for only 17 % of the total.

In general, conservation tillage has been most successful in Brazil and Argentina (Abrol et al. 2005) in the developing world. In these countries, 45–60 % of all agricultural land is said to be managed by conservation agriculture systems. In the 2001–2002 seasons, conservation agriculture practices are estimated to have been used on more than 9 million hectares in Argentina and 13 million hectares in Brazil. In Africa, the Africa Conservation Tillage Network (ACT) was established in 1998 to promote conservation agriculture as a sustainable means to alleviate poverty, make more effective use of natural and human resources, and reduce environmental degradation (Abrol et al. 2005).

Less labor, time, and cost are required under a reduced tillage system due to fewer tillage trips and cultivation operations for seedbed preparation. The savings range from \$2.47/ha to \$19.13/ha (Kimble et al. 2007).

- A large number of studies have estimated the potential fuel cost savings as a result of reducing tillage. They range between \$3.58/ha and \$28.29/ha (Kimble et al. 2007).
- Generally, reduced tillage systems have lower machinery repair and maintenance costs due to less use of tillage implements (Kimble et al. 2007).
- Zero-tillage technology reduces costs of field preparation up to US\$70 (Rs. 3,200) per hectare (Verma and Singh 2009), and it also saves time and labor (up to 10–20 %). A saving of fuel consumption by 26.5–43.7 l per hectare (Verma and Singh 2009) results in reduced fuel cost and reduced carbon emitted to the atmosphere.
- Zero-tillage can save farmers around 1 million liters of water per hectare (100 mm) compared with conventional practices due to the mulch on the soil surface which reduces evapotranspiration (Rehman 2007).
- Zero-tillage increases soil carbon from 0.1 to 0.7 metric tons ha^{-1} $year^{-1}$ (Paustion et al. 1995) under subtropical conditions.

13.1.3.2 Biochar

Biochar is a charcoal-like substance produced from agriculture and forest wastes. It has high active carbon surface area that is produced through anaerobic heating of biomass. Composition-wise, it contains 70 % carbon and the remaining elements are hydrogen, oxygen, and nitrogen. Biochar is used as soil enhancer to increase fertility, to prevent soil degradation, and to sequester carbon in the soil. It improves soil fertility by retaining water and nutrients in soil, encouraging beneficial soil organisms and thereby reducing the need for additional use of fertilizers. Biochar can store carbon in the soil for as many as hundreds to thousands of years. Biochar technology is different from the conventional charcoal production because it is highly efficient in the conversion of carbon and harmful pollutants are not released upon combustion. Hence, it is a cleaner and more efficient technology. If this technology is used sustainably, the by-products in the form of oil and gas can substitute for a cleaner and renewable fuel option.

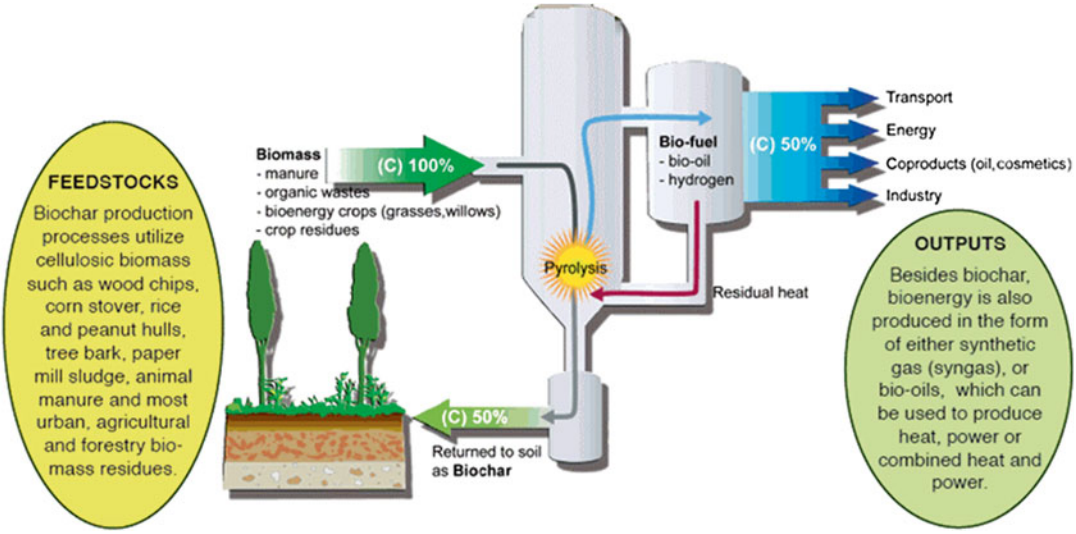

Fig. 13.6 Biochar production process (Source: The International Biochar Initiative (http://www.biochar-international.org/))

One of the simplest ways of making biochar is through the thermal decomposition of the biomass (waste from agriculture and forest). It can be done in three different ways, namely, pyrolysis, gasification, and hydrothermal carbonization. In all these processes, biomass is heated at a high temperature in the absence of air. This releases the volatile gases leaving behind carbon-rich biochar. During pyrolysis, a high proportion of carbon remains within the biochar giving it a very high recalcitrant nature. This increases the soil water- and nutrient-holding capacity (Chan and Zhihong 2009).

Biochar can be produced at small and large scales. Small-scale production can be through pyrolysis using modified stoves and kilns which are low cost and relatively simple technologies. For large-scale production, larger pyrolysis plants and adequate feedstocks are required which is more capital cost intensive (Fig. 13.6) (Pratt and Moran 2010).

The intensity of pyrolysis determines the product and by-product obtained from the process. For example, more bio-oil and syngas are obtained when fast pyrolysis is done at high temperature, while slow pyrolysis yields more biochar than by-products. Figure 13.6 demonstrates the biochar production through the pyrolysis process. This not only produces biochar but also produces clean energy like syngas and bio-oil which can be used for producing heat, power, or combined heat and power.

Biochar producing cookstoves are more popular in developing countries. The pyrolysis temperature of 450–500 °C might be difficult to attain in gasification stoves to make biochar. However, most of the stoves can produce 25–30 % of biochar (by weight) from the initial feedstock. This is the maximum weight of biochar that can be obtained from the slow pyrolysis process (Samuchit 2010). The most sustainable way of gathering feedstock for biochar would be to use the agricultural and forestry wastes. Biochar can be feasible in a small-scale industry like forest communities where woody biomass waste is readily available. Large-scale biochar production can be done through the cultivation of crops, but adequate land is required for its cultivation. The greatest economic potential of biochar for carbon sequestration can be realized if crop residues or waste biomass are used rather than purpose grown crops (Roberts et al. 2010). Biochar application has been introduced in Vietnam, Mongolia, and India, and cost-effective

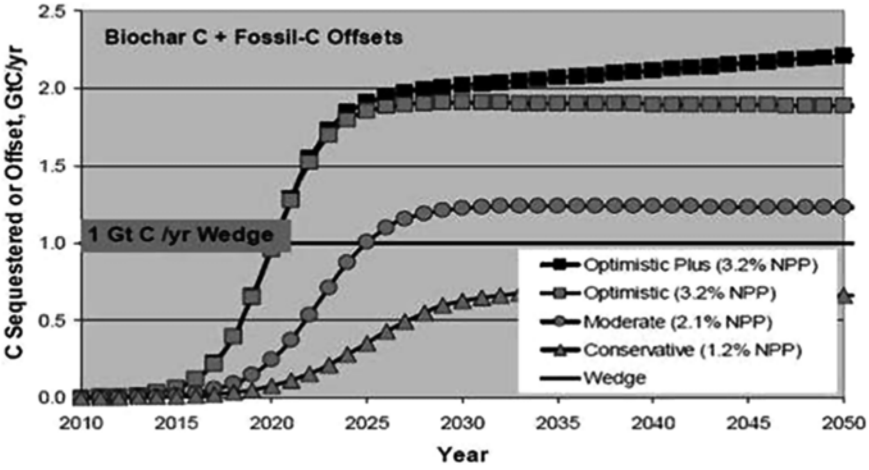

Fig. 13.7 Projection of carbon offset by biochar technology by 2050

approaches are being identified for widespread introduction of biochar in these countries.

The optimistic scenario in Fig. 13.7 shows that the use of biochar can sequester 2.2 gigatons of carbon annually by 2050. In agricultural soils, biochar has been experimentally shown to double grain yields, improve soil fertility, and increase water retention. Although modern biochar technology is still under research, some researchers claim that it has a significant potential for mitigating climate change together with generating social, economic, and environmental benefits.

The rice–wheat cropping system in the Indo-Gangetic Plains of India produces substantial quantities of crop residues, and if these residues can be pyrolyzed, 50 % of the carbon in biomass is returned to the soil as biochar. This would increase soil fertility and crop yields while sequestering carbon. In addition, pyrolysis of plant materials with applications of biochar to soil can actually result in a net carbon reduction from the atmosphere of 20 %, making it a carbon sequestering process (Lehmann 2007). It has been projected that about 309 million tons of biochar could be produced annually, the application of which might offset about 50 % of carbon emissions (292 teragram C year^{-1}) from fossil fuel (Lal 2005).

(i) *Advantages*
- Substantial amounts of carbon can be sequestered in a very stable form.
- The addition of biochar to soil has been associated with enhanced nutrient use efficiency, water-holding capacity, and microbial activity.
- In the process of manufacturing biochar, both heat and gases can be captured to produce energy carriers such as electricity, hydrogen, or bio-oil. Further, other valuable coproducts including wood flavoring and adhesives can also be obtained as a byproduct of biochar (Czernik and Bridgwater 2004).

(ii) *Disadvantages*
- Biochar applications sometimes disturb the physical and chemical balances of nutrients in the rhizosphere.
- Biochar generally helps the growth of undesirable weeds.
- Biochar manufacturing is relatively expensive.

Farmers can have an additional source of income through collection and sale of agri-residues.

- The grain yields in agricultural soils are shown to increase by the use of biochar.
- The use of locally available feedstock reduces dependence on fossil fuel.
- Employment opportunities can be created in the course of development of biochar technology.
- Revenue can be generated through carbon trading.
- Since biochar can be used as a fertilizer, alternative fertilizers no longer need to be purchased (imported) which helps developing countries to reduce trade and fiscal deficits.

(iii) Contribution of the technology to protection of the environment

(a) *Reduced GHG emission*: Reduced use of fertilizer results in reduced emissions from production and use of other fertilizer products. Retention of nutrients like nitrogen in the soil limits consequent emission of nitrous oxide into the atmosphere. As agricultural wastes are turned into biochar, the emission of methane resulting from natural decomposition of biomass is reduced. By 2100, the use of biochar can sequester 5.5–9.5 GtC/year (Lehmann et al. 2006). Similarly, biochar increases the microbial life in the soil and increases carbon storage in the soil.

(b) *Enhanced soil fertility and food security*: Biochar increases the number of soil microbes, retains nutrients in the soil, and hence increases the soil fertility and subsequently there is increased food security. In Laos, application of biochar improved saturated hydraulic conductivity of top soil. However, biochar may not be suitable for all situations. Derived biochar may enhance the loss of forest humus. Therefore identification of specific niches for biochar application is crucial to exploiting its benefits.

(c) *Reduced water pollution*: Groundwater and surface water pollution through leaching, erosion, etc., is reduced through lower use of chemical fertilizer and reduced degradation of soils. As the nutrients and agrochemicals are retained in the soil due to the use of biochar, pollutants produced through agriculture in water are reduced. Mizuta et al. (2004) notes that biochar can remove nitrate and phosphate from water. Biochar also has an affinity for organic compounds which can help retaining toxic organic compounds from water (Kookana et al. 2011).

(d) *Waste management*: Biochar technology offers a simple and sustainable solution to waste management because agricultural wastes are used as feedstocks. During the pyrolysis process, no waste is produced and by-products include syngas and bio-oils can be recycled and used further.

(e) *Reduced deforestation and increased cropland diversity*: Since biochar technology emphasizes the use of agricultural wastes as feedstock, deforestation is prevented and biodiversity inside soil can be significantly enhanced. Hence, by converting agricultural waste into a powerful soil enhancer with sustainable biochar, cropland diversity can be preserved and deforestation discouraged.

13.1.3.3 Off-Field Crop Residue Management

Crop residue management is an important mitigation technology using biomass, vermicompost, etc. processed under aerobic conditions which is being utilized as a commercial option to reduce greenhouse gas emissions. Vermicomposting is a modified method of composting using earthworms to eat and digest farm waste and turn it into a high-quality vermicompost in 2 months or less. It is different from other composts due to the presence of worms such as earthworms, red wigglers, white worms, etc. (Satavik 2011).

Crop residue management is an important component of organic farming that helps the conservation of carbon in the rhizosphere thereby mitigating the emissions of GHG to the atmosphere. It includes leguminous cover crops grown as green manure to provide a cost-effective source of N to subsequent crops. Organic farming relies heavily on inputs of organic residues in the forms of green manure (i.e., cover crops), plant compost, and composted animal manures added to the soil along with integrated

Table 13.2 Estimated crop residues in India 2006–2007 (Dixit et al. 2010)

Crop residues	Dry weight (million tons)
Cotton stalks	16.36
Maize cobs	2.72
Pigeon pea	6.93
Sunflower	2.46
Castor	1.41

biological pest and weed management, crop rotation, and mechanical cultivation to sustain and enhance soil productivity and fertility without the use of synthetic N fertilizer and pesticides (Table 13.2). The handling of crop residues also has an impact on net carbon gains. Removal of straw or stover can result in significant loss of soil organic carbon (SOC). If they are used as bedding for livestock, then much of the carbon may be returned to the soil as manure (Lal et al. 1998a).

Crop residue management through vermicomposting brings about 463 mg CO_2e m^{-2} h^{-1} compared to their anaerobic digestion value of 694 mg CO_2e m^{-2} h^{-1}. The experiments done by Chan et al. (2011) in Australian cities clearly confirm the reduction in GHG emissions through crop residue and vermicompost management. There will be ample opportunity for farmers to reduce GHG emissions in vermicompost production by reducing the use of chemical fertilizers which generally initiate the emission of N_2O and CH_4.

(i) *Advantages*

- When crop residue is incorporated into soil, the soil's physical properties and its water-holding capacity are enhanced.
- Organic residues and N fertilizers increase soil organic carbon and subsequently improve soil structure and aggregate stability. By stabilizing soil aggregates, soil organic matter is more protected from microbial decay (Six et al. 1999). The use of organic residue management cover crops and manures can lead to soil organic carbon accumulation by improving aggregation as well as reducing the need for synthetic fertilizer application while providing crops with equally adequate amounts of nutrients.
- The addition of organic residue to the soil reduces environmental pollution potential while maximizing the N use efficiency and providing crops with sufficient N.

Co-benefits of organic amendments applied to soil are a reduced need for herbicides by reducing weed emergence and enhancing soil quality, which provides better habitat for beneficial soil fauna. For example, decomposers such as earthworms can help in organic amendments. The castings and the channels that earthworms create improve root growth, water infiltration, and the physical structure of the soil. Earthworms also stabilize soil organic matter and contribute to the formation of stable soil aggregates.

(ii) *Disadvantage*

- The carbon and nitrogen mineralization rate of these manures and organic residues are relatively low for the recovery of N, which ranges between 5 and 18 % of total N for manures and 8 % for compost. Thus, these organic amendments would need to be applied in huge amounts in order to considerably increase the short-term N supply, which would lead to higher costs.

13.1.4 Water Management

About 18 % of the world's croplands now receive supplementary water through irrigation (Millennium Ecosystem Assessment 2005). Expanding the use of irrigation or using more effective irrigation measures can enhance carbon storage in soils through enhancing yields and residue returns. However, some of these gains may be offset by CO_2 from energy used to deliver the water or from N_2O emissions from higher moisture in the soil and increased fertilizer inputs. Quantifying these emissions requires additional research.

Cropland drainage in humid regions can also promote productivity, and hence soil carbon, and perhaps also suppress N_2O emissions by improving aeration. However, nitrogen loss through the drainage might be susceptible to loss as N_2O.

13.1.4.1 Irrigation

CO_2 emissions can be reduced with effective irrigation by increasing yields and crop residues which can enhance carbon sequestration (Smith et al. 2008). All types of irrigation, such as flood, sprinkler, surface, and subsurface drip, can all enhance crop yields with subsequent increases in crop residues and enhanced carbon sequestration. Eighteen percent of cropped areas are currently irrigated. If additional areas can be put under irrigation, then additional carbon sequestration can occur.

13.1.5 Rice Production Technologies

Most rice is grown in flooded paddy fields. When fields are flooded, the decomposition of organic material depletes the oxygen present in the soil and flood water which results in anaerobic conditions in the soil. Anaerobic decomposition of soil organic matter by methanogenic bacteria results in methane emissions. While part of the methane is oxidized by aerobic methanotrophic bacteria in the soil and part is leached away as dissolved methane in the flood water, the remaining unoxidized methane is emitted from the soil to the atmosphere.

As such, cultivated rice production results in significant emissions of methane by the soil. These emissions can be reduced by various practices:

- Draining wetland rice once or several times during the growing season reduces methane emissions. If water is drained and soils are allowed to dry sufficiently, CH_4 emissions decrease or stop entirely. However, this benefit may be partly offset by increased N_2O emissions, and the practice may be constrained by water supply.
- Rice cultivars with low exudation rates could also offer an important methane mitigation option. In the off-season rice, methane emissions can be reduced by improved water management. Methane emissions are reduced by keeping the soil as dry as possible and avoiding water logging.
- Increasing rice production can enhance soil organic carbon stocks.
- Adjusting the timing of organic residue additions can also reduce methane emissions. For instance, incorporating organic materials in the dry period rather than in the flooded periods reduces emissions.
- Composting the residues before incorporation reduces methane emissions.
- By producing biogas for use as fuel for energy production.

The US Environmental Protection Agency (US EPA) concludes that the water management system under which rice is grown is the most important factor affecting methane emissions. Also, the amount of available carbon susceptible to decomposition is also considered critical by the US EPA. In addition to water management, other practices (e.g., tillage, fertilization, manure amendments) will alter the soil environmental conditions (e.g., temperature, moisture, pH) and hence affect the soil carbon- and nitrogen-driving processes such as decomposition, nitrification, and denitrification. The changes in the soil biogeochemical processes will finally affect the availability of soil nitrogen and water to the crops and hence alter the crop yields. Because crop residue is the major source of soil organic carbon, the change in crop yield and litter will redefine the soil organic matter balance, which is one of the most important factors determining the CH_4, soil CO_2, and N_2O emissions.

Soil temperature is also known to be an important factor regulating the activity of methanogenic bacteria and, therefore, the rate of CH_4 production.

Rice cultivation is responsible for 10 % of GHG emissions from agriculture. In developing countries, the share of rice in GHG emissions from agriculture is even higher, e.g., it was 16 % in 1994. A variety of technologies are presented for reducing emissions from rice cultivation.

The following rice-related mitigation technologies are described:

- Fertilizer, manure, and straw management
- Water management: mid-season drainage
- Water management: alternate wetting and drying
- Potassium fertilizer application
- Agricultural biotechnology

- Reduced tillage
- Direct seeding
- Chemical fertilizer amendment
- Electron acceptors

13.1.5.1 Fertilizer, Manure, and Straw Management

Fertilizer and manure management in rice fields are important methane mitigation technologies. The fertilizer management mitigation option includes changes in fertilizer types, fertilizer nutrient ratios, the rates and timing of applications, and the use of nitrification inhibitors to reduce methane emissions by affecting methanogenesis in rice fields.

Nitrification inhibitors are known to inhibit methane oxidation (Bronson and Mosier 1994). Lindau et al. (1993) reported that some nitrification inhibitors can mitigate methane emissions from rice fields as well. They are, therefore, dual-purpose technologies for both N_2O and CH_4 mitigation.

(i) *Feasibility of technology and operational necessities*: The use of the nitrification inhibitors such as Nimin or placement of urea super-granule in flooded rice fields can be considered as suitable options for mitigation of methane emissions from rice fields without affecting grain yields where flood waters are deep (30 cm) but not shallow (5 cm) (Tables 13.3 and 13.4). These measures not only improve N use efficiency in lowland rice cultivation but also reduce methane emissions from deep-flooded rice fields.

Methane emissions were lowest in plots treated with a mixture of prilled urea and Nimin, a nitrification inhibitor which inhibits the autotrophic oxidation of NH_4^+ to NO_2. Lindau et al. (1993) reported that these nitrification inhibitors can significantly mitigate methane emissions from rice fields. In a micro plot study with dry-seeded-flooded rice paddies, the application of nitrification inhibitors, in particular nitrapyrin and wax-coated calcium carbide, retarded methane emissions considerably. The decrease in methane emissions in plots treated with wax-coated calcium carbide was attributed to a direct result of the slow release of acetylene, a known inhibitor of methanogenesis (Bronson and Mosier 1991). Lindau et al. (1993) also reported that nitrification inhibitors such as encapsulated calcium carbide and dicyandiamide – containing compounds $[(NH_4)_2SO_4$ and $Na_2SO_4]$ – had mitigating effects on CH_4 emissions from flooded rice cultivation.

Table 13.3 Methane efflux from deep (30 cm)-flooded lowland rice plots planted to cv. Gayatri, as influenced by fertilizer management (Rath et al. 1999)

	Methane efflux[a] ($mg\ m^{-2}\ h^{-1}$)				
	Days after transplanting (DAT)				
Treatment	30	50	70	85	100
Control	8.3a	21.0a	39.9a	90.7a	70.6a
Prilled urea	5.7a	13.1a	26.8a	67.2ab	62.8a
Prilled urea + Nimin	5.2a	17.7a	27.1a	48.0c	50.0b
Urea super-granule	6.1a	13.2a	30.7a	58.4c	52.6b

[a] Observations. In a column means followed by a common letter are not significantly different at the 5 % level by DMRT

Table 13.4 Plant biomass production and the cumulative methane efflux from shallow (5 cm)-irrigated and rainfed deep (30 cm)-flooded lowland rice fields planted with cv. Gayatri (Rath et al. 1999)

	Plant biomass production ($t\ ha^{-1}$)		
Treatment	Straw yield	Grain yield	Cumulative methane emission ($g\ m^{-2}$)
Deep (30 cm)-flooded field plots			
Control	8.38	5.04	347.5
Prilled urea	8.48	5.52	307.5
Prilled urea + Nimin	10.07	5.48	255.0
Urea super-granule	10.97	6.22	295.0
Shallow (5 cm) field plots			
Control	5.87	4.10	38.8
Prilled urea	7.37	4.90	73.8
Prilled urea + Nimin	8.51	5.60	70.0
Urea super-granule	8.19	5.80	116.3

The effectiveness of treatments for inhibiting CH_4 production in descending order are as follows: sodium azide > dicyandiamide (DCD) > pyridine > aminopurine > ammonium thiosulfate > thiourea. The inhibition of CH_4 production in

DCD-amended soils was related to a high redox potential, low pH, low Fe_2^+, lower mineral carbon content, and low population of methanogenic bacteria.

Several benzene-ring compounds (Patel et al. 1991) and N-containing compounds (Bollag and Czlonkowski 1973) are also known to suppress methanogenesis in pure cultures and in soils. Chemicals known to inhibit CH_4 production as well as CH_4 oxidation include DDT (2, 2-dichlor odiphenyltrichloroethane) (McBride and Wolfe 1971) and the nitrification inhibitor, acetylene (Sprott et al. 1982). The availability of these specific and general inhibitors of microorganisms holds promise for their use with chemical fertilizers or other agrochemicals to mitigate CH_4 emissions from rice soils. This opens up the possibilities of developing suitable management schedules for regulating methane emissions from flooded rice paddies.

The mineral N fertilizers generally reduce NH_4 emissions to varying degrees. In contrast, incorporation of organic sources, for instance, green manure and rice straw, in soils can stimulate methane emission (Denier van der Gon and Neue 1995). However, when compared to burning of the straw, the incorporation of rice straw before a wheat crop in Haryana (India) or vegetable crops in the Philippines and China has resulted in significant reductions of methane emissions (Wassmann and Pathak 2007). The average methane emissions were reduced by approximately 0.4 t CO_2e ha^{-1} compared to straw burning. However, the cost of field operations and the detrimental effects on upland crops make this option costly. Two other options of straw management are sequestration of straw in the form of construction material and feeding raw straw to animals. These options are being used in China, where high rice production results in large amounts of rice straw. The prices in China are US\$5.98 and US\$6.86 per t CO_2e, which is only half of the price in the Philippines and Haryana (India). However, in all these three cases, straw management options have a relatively high reduction potential that collectively accounts for 1.34, 1.87, and 1.36 t CO_2e ha^{-1} in the Philippines, India, and China, respectively. Another option is composting the straw before application, which can reduce CH_4 emissions under continuous flooding by 58 % compared to fresh straw under continuous flooding with no significant effect on yield (Wassmann et al. 2000).

(i) *Advantages*

1. Nitrogen fertilizer is needed for rice to reach its potential yield. These N treatments can supply the N while at the same time increasing C sequestration from the increased productivity.
2. Nitrification inhibitors can effectively improve fertilizer use efficiency while providing immediate and large reductions of methane emissions for a long period of time.

(ii) *Disadvantages*

1. To reach its maximum potential, the particular fertilizers and a supply of manure must be available at or just before transplanting time.
2. Nitrification inhibitors are expensive, may leave unacceptable residues in the soil, are only effective in certain soils, and may be lost by volatilization.

Pathak et al. (2011) have presented annual cost, returns, and wheat equivalent yield in the recommended N, P, and K (NPK) as well as recommended N, P, and K plus farmyard manure (NPK+FYM) in various long-term experiments carried out in different states of India using different cropping systems (Table 13.5). Their calculations show, for example, that the rice–wheat rotation in Haryana is far more productive and profitable than the other rotations, which would increase C sequestration at the same time. The addition of farmyard manure increased productivity in two-thirds of the cases, but decreased it in about one-third of the cases, so local adjustments would have to be made for the crop rotation in use.

Setyanto et al. (1997) reported that methane emissions from mineral fertilizers such as tablet urea, prilled urea, and $(NH_4)_2SO_4$ were affected by the method of application, i.e., those methods that involved incorporation of the fertilizer into the soil had lower methane emissions. The use of

Table 13.5 Annual cost, return, and wheat equivalent yield (WEY) in the NPK and NPK+FYM treatments in various long-term experiments (Pathak et al. 2011)

		NPK treatment		NPK+FYM treatment	
Cropping system	State	WEY[a] (Mt/ha)	Benefit–cost ratio	WEY[a] (Mt/ha)	Benefit–cost ratio
Rice–wheat	Meghalaya	4.6	1.6	7.1	2.4
Rice–wheat-–jute	West Bengal	9.2	2.3	7.8	1.9
Rice–wheat	West Bengal	4.1	1.2	5.0	1.4
Rice–mustard–sesame	West Bengal	6.6	1.6	8.1	1.9
Rice–berseem	West Bengal	3.4	1.2	3.9	1.3
Rice–wheat	Uttar Pradesh	7.6	2.6	7.6	2.5
Rice–wheat	Uttar Pradesh	7.1	2.4	6.2	2.0
Rice–wheat	Bihar	6.0	2.0	7.0	2.2
Rice–wheat	Uttar Pradesh	7.4	2.5	7.2	2.4
Rice–wheat	Uttarakhand	8.1	2.7	7.6	2.5
Rice–wheat	Punjab	6.5	2.8	7.6	3.1
Rice–wheat	Haryana	7.4	3.6	8.2	3.7
Rice–rice	Orissa	6.9	2.7	7.5	2.9

[a] *WEY* wheat equivalent yield

$(NH_4)_2SO_4$ as N fertilizer to replace urea also resulted in a 5–25 % decrease in CH_4 emissions.

As per Wassmann and Pathak (2007), the relative costs for mitigation through nitrification inhibitor were US\$6.4, US\$5.5, and US\$9.8 per t CO_2e saved in Ilocos Norte province (Philippines), Zhejiang province (China), and Haryana state (India), respectively. In Ilocos Norte and Zhejiang, the reduction potential was ca. 0.7 t CO_2e/ha, whereas this option only yields marginal emission savings (0.13 t CO_2e/ha) in Haryana.

If incentives are given in terms of C credits for mitigating global warming potential and subsidies for reducing N loss, farmers will adopt these technologies such as conservation tillage, soil test-based N use, and more precise placement of fertilizers on a large scale in South Asia (Ladha et al. 2009).

13.1.5.2 Mid-Season Drainage

Mid-season drainage involves the removal of surface flood water from the rice crop for about 7 days towards the end of tillering. It aerates the soil, interfering with anaerobic conditions and thereby interrupting CH_4 production. Mid-season drainage of a rice crop involves withholding flood irrigation water for a period until the rice shows symptoms of stress. It involves ridge and furrow cultivation technology, where some moisture still exists in the soil even after the toe furrow is drained. It is essential to check when the crop has used most of the available water. The degree of soil cracking will depend on the soil type and on the spatial distribution of the rice cultivars. The cumulative evapotranspiration of the crop varies from 77 to 100 mm during the time water is removed depending on crop vigor and soil types. The field is then re-flooded as quickly as possible. It is necessary to cover the soil surface with water so that the plants start recovery. Water depth then can be gradually increased to that required for protection of the developing plant canopy from damage with high temperatures during anthesis. Mid-season drainage reduces methane emissions of paddy fields, with reductions ranging from 7 to 95 % (Table 13.6).

However, rice is also a significant anthropogenic source of N_2O. Mid-season drainage or reduced water use creates unsaturated soil conditions, which may promote N_2O production. Mid-season drainage is an effective option for mitigating net global warming potential although 15–20 % of the benefit gained by decreasing

Table 13.6 Reductions in methane emissions due to various water management practices compared to continuous flooding (with organic amendments) (Wassmann et al. 2000)

Mitigation practices	Seasonal emissions (kg/ha)	Relative reduction (%)	Experiment location
Mid-season drainage	385	23[a]	Beijing 1995
	312	44 ns	Hangzhou 1995
	51	43[a]	Maligaya 1997 DS
	25	7 ns	Maligaya 1997 WS
Alternate flooding/drainage	216	61[a]	Hangzhou 1995
	207	59[a]	Beijing 1995
Mid-season drainage and no organic matter	26	95[a]	Beijing 1995
	239	57[a]	Hangzhou 1995

[a] Statistically significant

WS wet season, *DS* dry season, *ns* not significant

methane emission was offset by increasing N_2O emissions. Little N_2O emission occurred when fields were continuously flooded (Zou et al. 2005). Mid-season drainage, however, caused intense emissions of N_2O, which contributed greatly to the seasonal amount. After the mid-season drainage, on the other hand, no recognizable N_2O was observed when the field was frequently waterlogged by the intermittent irrigation. In contrast, large N_2O emissions were observed when the field was moist but not waterlogged by the intermittent irrigation. Thus, N_2O emissions during intermittent irrigation periods depended strongly on whether or not water logging was present in the fields. Different water regimes cause changes to N_2O emissions from rice paddies (Zou et al. 2005).

(i) *Advantages*

- Methane emission reductions associated with mid-season drainage in rice field range from about 7 to 95 % (Table 13.6) with little effect on rice grain yield.
- Draining stimulates root development and accelerates decomposition of organic materials in the soil making more mineralized nitrogen available for plant uptake.
- Mid-season drainage saves water, which could be used for other purposes.
- Mid-season drainage inhibits ineffective tillers and improves root activities.

(ii) *Disadvantages*

- Drainage has the unintended effect of increasing N_2O emissions. However, mid-season drainage can help mitigation of N_2O if a field was frequently waterlogged by intermittent irrigation.
- Intermittent drying or drainage of soil is not feasible on terraced rice fields because drying could cause cracking of the soil leading to water losses or, in extreme cases, complete collapse of the terraced construction.
- Field drainage also induces weeds and thereby reduces the rice grain yield.
- Mid-season drainage delays the development of crop. Flowering is generally delayed by 3–4 days, and harvest/maturity may be delayed by 7–10 days.
- Mid-season drainage may increase plant height, and this will make the crop more prone to lodging especially when grain yield is high.

According to Wassmann and Pathak (2007), mid-season drainage is a profitable mitigation technology due to low labor cost and low yield risk. The cost of the technology was around US$20 per t CO_2e saved. Nelson et al. (2009) observed that by one mid-season drying, net revenue dropped less than 5 % while GHG emissions dropped by almost 75 million metric tons of CO_2e (approximately 4,000 t CO_2e ha^{-1}).

13.1.5.3 Alternate Wetting and Drying

The International Rice Research Institute (IRRI) in the Philippines has developed a new mitigation

Fig. 13.8 A new mitigation technology for methane known as alternate wetting and drying

technology for methane known as alternate wetting and drying (AWD) (IRRI 2009) (Fig. 13.8). AWD is a water-saving and methane mitigation technology that lowland (paddy) rice farmers can use to reduce their water consumption in irrigated fields. Rice fields using this technology are alternately flooded and dried. The number of days of drying the soil in AWD can vary according to the type of soil and the cultivar from 1 day to more than 10 days.

Starting from about 15 days after transplanting, farmers using AWD stop irrigating until the water table goes 15 cm below the ground level. A 20 cm hole is dug in the rice field, and a perforated plastic pipe is installed to monitor the level of the water table after each irrigation (Fig. 13.9). This practice is continued until flowering starts. At that time, it is necessary to keep 2–4 cm of standing water from flowering to dough stage.

This technology is very common in countries such as China, India, and the Philippines (IRRI 2002).

(i) *Advantages*

  - Large reductions in methane emissions are possible compared to continuous flooding (Table 13.6).
  - It will help the economic use of water during rice cultivation.
  - The drying phase of rhizosphere will help root growth and its sustainability for water transport to rice plants even under low soil moisture conditions.

Fig. 13.9 Alternate wetting and drying (AWD) technology for methane mitigation. The water table level has been lowered to the stress stage (15 cm depth) so that it is time to flood the field again (IRRI 2009)

  - Farmers will be able to know the status of water of their rice-growing fields and would be able to balance irrigation with achieving minimum methane emissions.
  - The savings of irrigation water will have impact on environment because of reduced withdrawal of groundwater and a reduction in consumption of diesel for water pumps.
  - The protection of water levels of groundwater may also reduce arsenic contamination in rice grain, and straw.

AWD technology can reduce the number of irrigations significantly compared to farmer's

Table 13.7 Effect of K fertilization on methane emissions from a rice field (Babu et al. 2006)

K level	Biomass (g/m^2)		Cumulative CH_4 (kg/ha)	Kg CH_4/mg grain yield
	Aboveground	Underground		
Control (K_0)	1,419.21a	189.64a	125.34	25.32
K_{30}	1,562.90ab	252.23bc	63.81	11.00
K_{60}	1,557.65ab	236.32b	82.03	14.34
K_{120}	1,671.00b	287.03c	64.43	10.70

Note: In a column, means followed by a common letter are not significantly different ($P<0.05$) by Duncan's multiple range test

practice, thereby lowering irrigation water consumption by 25 %, reducing diesel fuel consumption for pumping water by 30 l per hectare, and producing 500 kg more rice grain yield per hectare.

The visible success of AWD has dispelled the concept of yield losses under moisture stress condition in non-flooded rice fields. The adoption of AWD technology reduced water use and methane emissions, and it increased rice productivity. It can reduce methane emissions by 50 % as compared to rice produced under continuous flooding.

(ii) *Disadvantages*

- Occasionally, rice productivity is reduced using AWD technology if moisture stress condition is induced. However, the reduction of yield was less compared to the yield reduction due to the direct moisture stress effect.
- N_2O emissions are increased.

13.1.5.4 Potassium Fertilizer Application

Fertilization with muriate of potash (MOP) can significantly reduce emissions of methane from flooded soils planted with rice. Potassium applications to rice field soils prevent a drop in redox potential and reduce the contents of active reducing substances and Fe_2^+ contents. Potassium amendments also inhibit methanogenic bacteria and stimulate methanotrophic bacterial populations. In addition to producing higher rice biomass (both above- and belowground) and grain yield, potassium amendments can effectively reduce CH_4 emission from flooded soil, and this could be developed into an effective mitigation option especially in potassium-deficient soils (Babu et al. 2006) (Table 13.7).

(i) *Advantages*

- Chemical fertilizers mitigate methane emissions more quickly compared to the slow processes of organic amendments.
- Chemical fertilizers also fulfill the nutrient requirements of crops, thus helping in sustaining productivity while mitigating methane emissions.
- Chemical fertilizers sometimes improve soil health if used with care to maintain nutrient balance in soil.

In potassium-deficient soils, applications of potassium fertilizer generally increase yields significantly; the value of the increase in yield exceeds the costs of the fertilizer treatments. Therefore, under these conditions, the reduction in methane emissions is an added benefit whose mitigation cost is effectively zero. In addition, K fertilization can reduce methane emissions by half.

(ii) *Disadvantages*

- The potassium fertilizer must be precisely applied in order to avoid negative effects on field fertility.
- Chemical fertilizers that are applied in excess to the normal ratio generally change the nutrient composition of the soil besides affecting their physical structure. This affects adversely both methane oxidation and methanogenesis.

13.1.5.5 Agricultural Biotechnology

To identify the use of rice cultivars with reduced methane emissions, Wang et al. (2000) demonstrated that rice cultivars with small root systems, high root oxidative activity, high harvest index, and productive tillers are likely to produce less methane than other cultivars. They have identified cultivar Zhongzhou (modern japonica) as less methane-emitting compared to Jingyou (japonica hybrid) and Zhonghua (tall japonica). Parashar and Bhattacharya (2002) identified Annada rice variety (commonly used in Andhra Pradesh, a major rice-growing region in India) as high yielding, with comparatively low methane emissions. Although low methane-emitting rice cultivars have been identified, methane emission reductions due to cultivar selection have been shown to be less significant than those identified due to modifying water management regimes or adding organic amendments. In addition, the rice yield of low methane-emitting cultivars needs to be evaluated. If the low emitting rice cultivars produce less rice, then more rice would need to be cultivated to meet demand, and as a result, overall methane emissions may increase.

Methane emissions can be reduced by selecting rice cultivars like "Luit" which transport a large portion of their photosynthates to panicle growth and grain development (high harvest index). Varieties like "Disang" should be avoided which use their photosynthates for the development of vegetative parts such as roots, leaf sheaths, culm, etc. (low harvest index) that later on contribute to the emission of methane (Das and Baruah 2008).

Methane emissions can also be reduced by selecting cultivars like "Prafulla" and "Gitesh" which have slower transport of methane due to smaller cross-sectional areas of their medullary cavities. Das and Baruah (2008) recorded a positive correlation between methane flux and the size of medullary cavity. They observed that the rice varieties "Basmati" and "Bogajoha" with larger sizes of medullary cavities had greater cross-sectional areas with higher methane diffusion pathways. Uprety et al. (2011) reported that methane concentration in the medullary cavities of rice plants is about 2,900 times higher than that of ambient air.

Important plant anatomical parameters such as leaf number, tiller number, and plant biomass, which regulate the emission of methane, are identified. Modification of these anatomical traits, as well as possible changes in physiological processes, can help rice breeders develop new low methane-emitting genetic lines of rice and developing site-specific technology packages, ascertaining synergies with productivity and accounting for methane emissions.

The biotechnology approach for methane mitigation technology involves identification of rice cultivars which emit less methane. It also involves the tailoring of plants which translocate less photosynthates to the roots and more to reproductive parts.

(i) *Advantages*
  - Farmers have exclusive choice of designing and selecting low methane-emitting rice cultivars with high yield without altering the farming operations.

(ii) *Disadvantages*
  - Methane emissions are not normally measured by rice breeders, so this would require additional effort, although if some anatomical traits are sufficiently well correlated with methane emissions, then the extra effort might be minimal.
  - The degree to which emissions can be lowered using this approach may not be large.
  - Varieties with the low emissions trait may be lower yielding.
  - Considerable time is required to develop new varieties.

13.1.5.6 Reduced Tillage

For upland crops, reduced tillage technology for paddy rice involves planting or transplanting directly into the soil with minimal prior tillage in the residues of the preceding crop.

Methane emissions at the tilling stage of rice field preparation account for more than 80 % of total annual emissions. Wetland tillage compared to dryland zero-tillage results in an earlier onset of methanogenesis and, therefore, contributes to greater methane production during the growing season. Zero-tillage results in the lowest methane emissions and is a practice which utilizes crop residues in place of compost or mulch. This is often done by hand transplanting, but mechanical rice transplanters that can transplant small seedlings into flooded soil are becoming popular in developed countries like Japan and South Korea.

Following about a week after a herbicide application, broadcasting of pre-germinated seeds into the flood water is also done (Huang et al. 2012).

Zero-till for paddy rice production is not widely practiced. Zero-till with its more costly machinery has become prevalent only in richer countries whose farmers can afford equipment like mechanical transplanters. However, use of herbicides has enabled broadcasting of pre-germinated seed, but lack of familiarity with reduced tillage techniques is a major constraint for small, poor farmers.

(i) *Advantages*
- Less labor required.
- Farmers do not require as much time for the preparation of the field for the next crop.
- As less time is required for field preparation, water can be conserved or alternatively, the plant growth period can be lengthened, allowing the use of longer-season varieties with higher yield potential.
- Methane mitigation through reduced tillage provides protection of the soil and improves its condition.

(ii) *Disadvantages*
- Rice cultivation under reduced tillage makes it vulnerable to harmful pests such as the stem borer which survive on the unincorporated residue or stubble.
- Deploying new machinery for reduced tillage and training to farmers is a long-term endeavor and involves considerable expenditure.
- Minimum tillage practices require increased use of herbicides and are, therefore, less acceptable.
- Lower germination with reduced tillage necessitates higher seeding rates and therefore higher seed costs.

13.1.5.7 Direct Seeding

Pre-germinated seeds or seedlings are directly planted in soil (Fig. 13.10) or broadcast in flooded field under this technology.

Direct seeding of pre-germinated rice has resulted in reduced methane emissions due to a shorter flooding period and decreased soil disturbance compared to transplanting rice seedlings. Ko and Kang (2000) demonstrated that in South

Fig. 13.10 Direct planting of pre-germinated paddy seeds in soil

Table 13.8 Economics of wet-seeded rice in Sri Lanka (Weerakoon et al. 2011)

Region	Total input\ costs (US$/ha)	Gross returns (US$/ha)	Profit (US$/ha)
Dry zone irrigated	523	865	342
Intermediate zone irrigated	551	731	181
Wet zone rainfed	538	426	−112

Korea, where the common cultural practice is to transplant 30-day-old seedlings, significant reductions in methane emissions could be achieved by direct seeding on wet soil (8 %) and on dry soil (33 %) with no significant effect on yields in either case. Similarly, Metra-Corton et al. (2000) showed that direct seeding resulted in a 16–54 % reduction in methane emissions compared to that of transplanted rice seedlings. For six different cases, Wassmann et al. (2000) reported a 16–92 % reductions in methane emissions with direct seeding compared to transplants, for six rice cultivars; however, yield reductions of 4–36 % was also observed. Subsequently, Huang et al. (2012) found no significant effect on yield over six growing seasons, when a treatment of no-tillage + herbicide + broadcast of pre-germinated seeds on flooded field was compared to conventional tillage + later flooding + transplants, but at the end of the fifth year, increased in organic carbon in the top 5 cm of soil was approximately matched by reductions in carbon at deeper depths.

(i) *Advantages*
  - Direct planting is faster and less labor-intensive than transplanting.
  - It reduces land preparation time.

(ii) *Disadvantages*
  - Yields reduced in some instances (Hossain et al. 2002)
  - More lodging of rice plants (De Datta 1986)

Weerakoon et al. (2011) surveyed Sri Lankan farmers and presented the cost of cultivation for direct wet-seeded rice in three scenarios: dry zone irrigated, intermediate zone irrigated, and wet zone rainfed (Table 13.8). They found that under irrigated conditions, direct seeding was profitable, whereas under rainfed conditions, gross returns were about half than under irrigation, and the direct seeded cropping system was not profitable.

According to Wassmann and Pathak (2007), costs of emissions saving through direct seeding was found to be more than US$35 per t CO_2e saved.

13.1.5.8 Chemical Fertilizer Amendment

Emissions of GHGs are affected by the amounts and types of fertilizers applied, so judicious choice of fertilizer application rates and fertilizer types can reduce emissions. The source, mode, and rate of application of mineral fertilizers influence CH_4 production and emission from flooded rice paddies. CH_4 emissions from rice fields were decreased by 18 % due to chemical fertilizer amendments (Minami 1995).

Increases in rice production in South Asia have been attributed to increased nitrogen use. Increased nitrogen use may also have an additional benefit of lowering methane emissions. Incorporating urea into soil has been shown to reduce methane emissions. However, surface-applied urea resulted in 20 % more emissions compared to an unfertilized field. The use of sulfate-based fertilizer has also been linked to methane emission reductions. Metra-Corton et al. (2000) reported that ammonium sulfate reduced methane emissions by 25–36 % in rice fields. Applying phosphogypsum (calcium sulfate dihydride) in combination with urea reduced methane emissions by more than 70 %. Application of sulfate-containing fertilizers reduced methane emissions from flooded rice fields (Adhya et al. 1998). In contrast, incorporation of organic sources, for instance, green manure and rice straw, in soils stimulates methane emission (Denier van der Gon and Neue 1995).

Foliar application of nitrogenous fertilizer is another potential mitigation practice for reducing CH_4 emissions from rice soils (Kimura et al. 1992). Adhya et al. (1998) demonstrated a large inhibition of CH_4 production and emission by an application of single superphosphate and a smaller inhibition by an application of rock phosphate. They attributed this inhibitory effect to the high PO_4^{2-} content of the P fertilizers. Nitrification inhibitors (thiourea, sodium thiosulfate, and dicyandiamide) inhibited the CH_4 emission activity of flooded rice field soil (Bronson and Mosier 1994).

Rath et al. (1999) found that the subsurface application of urea super-granules was marginally effective in reducing the CH_4 flux relative to that in untreated control plots. Bronson and Mosier (1994) reported that N fertilizers inhibit methanotrophic microorganisms in soils. Generally, fertilizers with an ammoniacal form of N (NH_4^+-N) increase CH_4 emissions.

In principle, three different causes have been suggested for the inhibitory effect of nitrogenous fertilizers, especially NH_4^+-N fertilizers, on CH_4 oxidation which results in increased emissions of CH_4:

- An immediate inhibition of the methanotrophic enzyme system
- Secondary inhibition through the NO_2 – production from methanotrophic NH_4^+ oxidation (Megraw and Knowles 1987)
- Dynamic alteration of microbial communities of soil (Powlson et al. 1997)

(i) *Advantages*
   - Crop growth and yields are stimulated, while emissions are reduced compared to fertilizers without mitigation potential.

(ii) *Disadvantages*
   - Fertilizers with higher mitigation potential may cost more.
   - Economics and mitigation potential.

According to Wassmann and Pathak (2007), rice production without organic amendments demonstrated the technical feasibility of reducing emissions at relatively low costs.

The addition of phosphogypsum is an efficient strategy to reduce emissions. Its actual costs varied from US$ 1.5 to 2.5 per t CO_2e saved in the Philippines and China, respectively, and the reduction potential is approximately 1 t CO_2e ha^{-1}. However, the relative cost for phosphogypsum application in Haryana (India) was higher (US$5 per t CO_2e saved), and the reduction potential was 0.29 t CO_2e ha^{-1}.

13.1.5.9 Electron Acceptors

According to Lueders and Friedrich (2002), methane emissions from paddy fields can be reduced by the addition of electron acceptors to stimulate microbial populations that compete with methanogens. Under ferrihydrite amendment, acetate was consumed efficiently (<60 μM), and a rapid but incomplete inhibition of methanogenesis occurred after 3 days.

Methanogenesis can be suppressed by the supplementation of alternative electron acceptors such as Fe (III) or sulfate, when electron donors for respiratory processes become limiting (Achtnich et al. 2005). This mitigation strategy is based on the thermodynamic theory which predicts that the energetically more favorable electron acceptor will be utilized first under substrate-limiting conditions (Zehnder and Stumm 1988). Microorganisms which can reduce the energetically more favorable electron acceptor [e.g., nitrate, Fe (III), sulfate] will outcompete those using a less favorable electron acceptor (e.g., CO_2).

Functional shifts can occur within a rice field soil microbial community by supplementing alternative electron acceptors in the form of ferrihydrite and gypsum, and thereby respiratory processes other than methanogenesis are promoted. Under gypsum addition, hydrogen was rapidly consumed to low levels (~0.4 Pa), indicating the presence of a competitive population of hydrogenotrophic sulfate-reducing bacteria (SRB). This was paralleled by a suppressed activity of the hydrogenotrophic RC-I methanogens as indicated by the lowest SSU rRNA quantities. Full inhibition of methanogenesis only became apparent when acetate was depleted to non-permissive thresholds (<5 μM) after 10 days.

The enhanced activity of FRB (Ferric iron-reducing bacteria) and SRB (sulfate-reducing bacteria) resulted in almost complete inhibition of methanogenesis under conditions of limiting substrate and non-limiting electron acceptor availability. Considering the electron uptake potential of eight electrons per CO_2 and SO_4^2 and one electron per Fe^{3+}, only the amount of sulfate reduced perfectly matched the quantity of methane which was not produced under inhibition. FRB also participates in the oxidation of electron donors other than acetate and H_2, thus limits its properties of reduction in methanogenesis. This may be another reason for the lower efficiency of inhibition of methanogenesis under ferrihydrite amendment. It was also demonstrated by Lueders and Friedrich (2002) that although the mitigating agent such as gypsum is added in the soil about one-tenth that of the ferrihydrite amendment, still the mitigation effects were comparable: 69 % and 85 % methane reduction, respectively.

(i) *Advantage*
  - Methane emissions can be reduced.

(ii) *Disadvantage*
  - The approach is still at the experimental stage.

The technologies of conservation tillage, midseason drainage, and alternate flooding reduced GHG emissions without extra expenditure. Higher net return with these technologies suggests the tremendous potential scope of their adoption by farmers.

Water management is often considered a good strategy to mitigate methane emissions from rice fields. Water-saving technologies can reduce methane emissions in a given area of rice land. The saved water will then be used to irrigate more land and new crops in future seasons. Rice is grown on more than 140 million hectares worldwide. Ninety percent of rice fields are temporarily flooded, providing scope for better water management to reduce water consumption, related energy and electricity consumption, and fertilizer consumptions. These reductions would result in methane mitigation and could then be included for claiming carbon credits.

13.1.6 Manure Management

Livestock manures represent a valuable resource that, if used appropriately, can replace significant amounts of chemical fertilizers. However, unless animal manure is managed carefully to minimize odor, nutrient losses, and emissions, it becomes a source of pollution and a threat to aquifers and surface waters. Animal manures can release significant amounts of N_2O and CH_4 during storage. Methane emissions from manure stored in lagoons or tanks can be reduced by cooling, use of solid covers, mechanically separating solids from slurry, or by capturing the CH_4 emitted. Economic growth and changing lifestyles in some developing countries are causing a growing demand for meat and dairy products, notably in China where current demands are low.

The most known technology for manure management is the anaerobic digestion, which is a process in which organic matter from wet organic wastes (i.e., liquid manure) is converted into methane by bacteria in the absence of oxygen (Fig. 13.11). The methane is then collected and may be used to generate electricity. In addition, the anaerobic digestion process creates potentially valuable by-products, such as the solids fraction – fiber – and liquid with available nutrients.

Another common technique is the aerobic digestion, which is useful in treating liquid manure for odor reduction, chemical oxygen demand (COD) and biochemical oxygen demand (BOD) reduction, and pathogen control. Aerobic treatment is usually a batch processor, semicontinuous (batch feed). In a batch process, all of the treated material is removed from the facility before refilling with untreated slurry. In a batch feed or semicontinuous process, some of the treated material is displaced by the addition of untreated material to the digester (Fig. 13.12).

A third method widely applied in the agricultural sector worldwide is composting, which is an aerobic digestion process used for solid wastes. Slurries or separated solids can be composted if mixed with a carbon source such as straw, peat, or wood shavings. However, composting slurry without separating the solids requires a great deal of additional material to retain the liquid. This would be very impractical due to the cost of the material and the energy required to turn the compost. Composted manure is a premium organic fertilizer and holds some potential as a marketable product in the gardening and landscaping market.

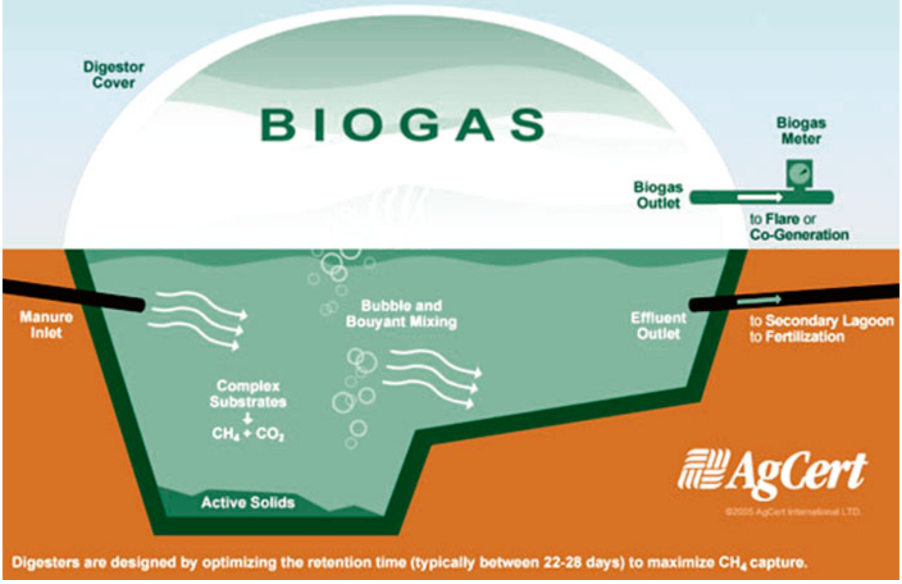

Fig. 13.11 Anaerobic digestion (Source: AgCert)

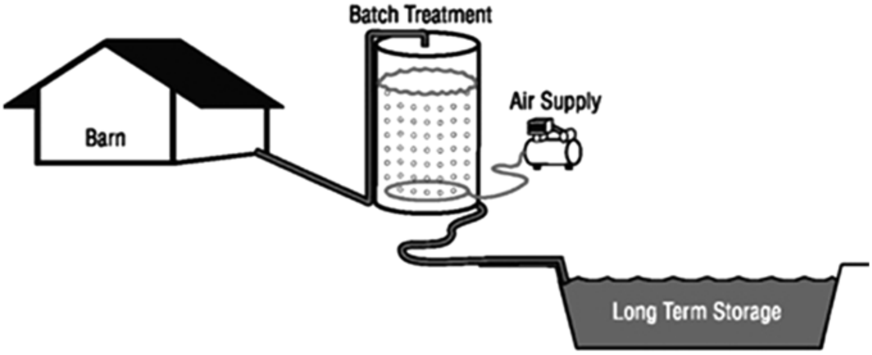

Fig. 13.12 Aerobic digestion (Source: Government of Alberta, Agriculture and Rural Development)

For some markets, and even some on-farm application techniques, the compost would have to be pelleted so that the nutrient content could be upgraded to a specific blend with commercial fertilizers.

Based on the IPCC (2007c), for most animals, worldwide, there is limited opportunity for manure management, treatment, or storage; excretion happens in the field and handling for fuel or fertility amendment occurs when it is dry and methane emissions are negligible (Gonzalez-Avalos and Ruiz-Suarez 2001). To some extent, emissions from manure might be curtailed by altering feeding practices or by composting the manure, but if aeration is inadequate, CH_4 emissions during composting can still be substantial (Xu et al. 2007).

Technologies in manure management are developing rapidly, and several countries in the developing world are implementing them to a certain extent. According to Brandjes et al. (1996), manure management systems are highly diverse, among which the following can be distinguished:

13.1.6.1 Grazing

Substantial losses through leaching may occur due to the uneven distribution of feces and urine (urine patches may have N load equal to 200–550 kg/ha). Volatilization of N may also be considerable (10–25 %), but less important since a part is deposited on nearby areas, though some of it on nonagricultural land.

13.1.6.2 Kraals

These enclosures are often used as in situ fertilization of arable land by moving the kraal regularly. Soil fertility of a larger area, used for grazing, is partially concentrated on the arable land, thus enabling crop production in resource-poor situations. Losses through leaching will be slightly higher than during grazing as equivalent N and K fertilization rates are increased.

13.1.6.3 Dry Lot Storage

If urine is not collected and bedding is sparsely used, losses of N and K in particular will be high as most urine is lost. Depending on the storage facilities and storage time of the feces, part of the nutrients in feces will also be lost through leaching and surface runoff, in the case of a precipitation surplus and uncovered manure heaps. Urine collection will minimize K losses, but N losses will often remain high as volatilization will increase, though this is dependent on climatic conditions, storage time, and storage method. Using bedding, with sufficient absorption capacity to capture urine, might reduce N losses with ca 15 % of the mineral N.

13.1.6.4 Slurry Storage

This system of manure storage, where feces and urine are stored together, is the main system in intensive livestock systems in OECD countries, except for broilers. Volatilization losses are dependent on the level of ventilation, depth of storage tanks, and storage time, but often range between 5 and 35 % of the total N excreted.

13.1.6.5 Lagoons

Lagoon systems are quite common at large livestock farms in Eastern European countries and, to a lesser extent, in Asia, while their importance is growing in the USA. Liquid manure, either before or after separating part of the solids, is treated in anaerobic lagoons. Organic material is decomposed, thereby mineralizing part of the nutrients. The liquid phase is either discharged into surface water or used for irrigation. The main problems are related to the discharge into surface water, leaching through the lagoon bottom, and odor. High NH_3 emission will occur as a major part of the N in mineral form, while also high CH_4 and N_2O emissions are also common.

13.1.6.6 Plastering Material for House Construction

This is particularly important in Africa; however, the amount of manure involved on a global scale is considered to be too insignificant to be discussed here. In this system, all nutrients are lost for agriculture.

13.1.6.7 Fuel

In many developing countries, and particularly in India, manure is an appreciable fuel. If burnt directly, most of the C and all the N and S will be lost; other nutrients may be recycled to arable land via the application of the ash. The production of biogas from manure is another method to valorize the energetic value of manure. The high water content of the slurry makes it more difficult to handle, and N losses via volatilization may be high, because most N in slurry is in mineral form. Though strongly promoted (in China) and applied to some extent in Asia, its present application is still limited mainly due to high investment costs (both for the digester and adjoining equipment) and technical problems.

13.1.6.8 Feed

Manure could be recycled by feeding it to animals, both livestock and fish, but this practice is limited. In addition to widespread reluctance to use manure as feed, probably originating from fear of health hazards, this can be explained by the low nutritive value of most types of manure, except for poultry manure as ruminant feed which is of a reasonable quality (ca 55–60 % TDN, 20–30 % CP). Consequently, in intensive production systems where collectable manure is abundant, more economic feed is available, while in production systems where the use of low quality feeds is common, high collection costs and/or opportunity costs (manure as fertilizer or fuel) are prohibiting the use of manure as feed.

In addition, biogas produced from the anaerobic digestion of animal manure, green crops, and other forms of organic waste can be used for heat and power generation as well as for transport fuels – after scrubbing to remove CO_2 and H_2S (IEA 2008). Several research programs exist, which aim at diffusing information and best practices for manure management.

According to the IEA (2008), the use of residues and waste as biomass can reduce farmers' costs and provide them with additional income. Based on IPCC (2007c), an appropriate mix of rice cultivation with livestock, known as integrated annual crop–animal systems and traditionally found in West Africa, India, Indonesia, and Vietnam, can enhance net income, improve cultivated agroecosystems, and enhance human well-being. Such combinations of livestock and cropping, especially for rice, can improve income generation, even in semiarid and arid areas of the world. Furthermore, a greater demand for farmyard manure can create income for the animal husbandry sector where usually poorer population deals with. There are other benefits from managing manure properly. Properly managed feedlots, manure stacks, and manure spreading can minimize nutrients entering surface waters and impacts downstream. Nutrient-rich waters promote excessive algae and aquatic plant growth which reduces wildlife habitat and recreational activities and may increase water treatment costs. In addition, bacteria and other pathogens may enter surface waters with runoff causing other human health concerns. With proper management, these adverse environmental impacts can be minimized.

The effect on the environment of the manure produced in a particular agricultural system should be assessed by considering its role in the total nutrient management of the system. If the import and export of nutrients in the system is in balance and animal manure is to play a positive role, it implies that losses from animal manure must be minimal. It also implies that efficient use is made of the manure in crop production, i.e., a large fraction of the nutrients from the manure is taken up by the crop. Another example is with the aerobic treatment, which can control dangerous bacteria such as *Cryptosporidium* and *Salmonella*, and they cannot exist in the presence of oxygen. On the downside, aerobic treatment can cause excessive loss of nitrogen as nitrogen gas, nitrous oxide, or even ammonia if excessive aeration rates are used. This loss of nitrogen to the atmosphere can create concerns of acid rain in some instances. Another concern is the potential loss of the economic value as nitrogen fertilizer.

Land application of raw or composted manure can be tailored to reduce the emission of GHGs and their impact on the environment. Application of more nitrogen than a crop needs via manure will result in excess nitrogen accumulation in soil and will increase the release of nitrogen as nitrous oxide. Application of manure at the wrong time of year, for example, in the very early spring, will also increase the release of nitrous oxide, as will applying raw manure during wet conditions. Researchers believe that timing manure application correctly and ensuring proper application amounts will contribute to an overall reduction in GHG emissions from agricultural operations.

The US EPA (2006) forecast that combined methane emissions from enteric fermentation and manure management will increase by 21 % between 2005 and 2020, taking into account that the global livestock-related methane production is expected to increase by 60 % up to 2030.

13.1.6.9 Covering Manure Storage Facilities

By covering manure with materials of a certain thickness (such as plastic sheeting, organic matter, and expanded clay), the manure's surface in contact with air is altered. This method can reduce the emission of GHGs and store nutrients in the manure.

Generally, covers are classified as impermeable or permeable. Impermeable covers do not allow gases coming from the manure to be emitted to the atmosphere. Permeable covers permit the transmission of some gases. Permeable covers usually include straw, geotextile, expanded clay, cornstalk, etc. The impermeable covers include floating plastic, suspended plastic, concrete, etc. Impermeable covers offer the opportunity to collect and use methane gas for fuel and power generation. A covered lagoon is a good example of a manure storage basin with an impermeable cover. It is a large anaerobic lagoon, which can stably digest manure, reduce odor, and supply nutrient-rich effluent for application on fields and crops. Pathogens and weed seeds are reduced, and biogas can be produced for use on the farm.

The effects on GHG emissions reduction vary for different covering materials and techniques. The principles of emission reduction are also different. For instance, impermeable materials such as plastic sheets can isolate manure from the external environment, thereby preventing loss of volatilized gases into the air. An anaerobic environment is also created within the manure. Since the first stage of N_2O generation is the aerobic nitrification reaction of ammoniacal nitrogen, the adoption of manure covering technology prevents exposure to oxygen. By stopping this first reaction, N_2O emissions are lowered.

Factors, such as temperature, moisture content, and pH, of the manure also have a significant impact on the mitigation effect of storage covering technologies. The moisture content of manure greatly affects the generation of CH_4. When the moisture content is high, anaerobic fermentation dominates, with greater production of CH_4 and less production of CO_2. When the moisture content is low, aerobic fermentation dominates, with CO_2 generated as the major fermentative products and basically no CH_4 is generated. The moisture content also affects nitrification and denitrification of manure. Neither extremely good nor poor permeability is conducive to the generation of N_2O in nitrification or denitrification processes. Therefore, in both cases of very low moisture content of animal manure and longtime submergence under water, N_2O emissions are very low. However, the dry–wet alternation of manure promotes the generation and emission of N_2O. Suitable pH environments vary for different microorganisms. In this sense, adjusting the pH value of liquid manure to affect the process of biochemical reaction and then lower the GHG emissions is another approach for emission mitigation.

13.1.6.10 Advantages

- The advantages are low cost, simplicity of operation, and ease of implementation.
- Commonly used materials such as straws, expanded clay, thin films, etc. are low cost and readily available. This makes it possible for animal farms to change the storing method of manure easily and conveniently.

13.1.6.11 Disadvantages

Covering and compacting manure creates an anaerobic environment within manure, which increases methane emissions although the generation of nitrous oxide is inhibited, i.e., a case of swapping one form of pollutant for another (Monteny et al. 2006).

The potential for emission reductions is greatly affected by manure properties, temperature, and other factors for which there is currently limited understanding. Different covering materials should be selected for solid and liquid manure. Many experimental results indicate that covering liquid manure with organic matter, including straw, will greatly increase the amount of methane emissions, generating more methane in anaerobic fermentation of straws instead of reducing emissions. To adapt to the differences in climatic types (temperature, precipitation), manure properties, and covering materials, experiments should be conducted to analyze and test the potentials of various combinations of these parameters to reduce greenhouse gas emissions.

Chadwick (2005) conducted an experiment to test the impact of compaction and covering methods of cattle manure on GHG emissions. Experimental results showed that compaction and covering with plastic film can reduce emissions of ammonia and N_2O from manure by 90 % and 30 %, respectively. However, compaction and coverage created an anaerobic environment inside the manure, increasing the amount of methane emissions (Chadwick 2005).

Additionally, by decreasing the surface area of the manure heap and by timely transport of manure to an enclosed storage chamber, the amount of NH_3 and CH_4 emissions can be reduced effectively (Weiske et al. 2006).

Generally, reducing ammonia volatilization and preventing odor can be achieved by covering liquid manure with straw, which may also increase methane emissions. Berg and Pazsiczki (2006) achieved GHG emission reductions by combining straw coverage with an acidizing technique. Experimental results showed that methane emissions were reduced by 40 % by adjusting the pH value of liquid manure to less than 6 with lactic acid and integrated covering with straws.

A hard crust is naturally formed during the storage of manure, which prevents ammonia produced by manure from escaping. An experiment by Smith et al. (2007) showed that ammonia emissions from manure with naturally formed crust can be reduced by over 60 % compared to the emissions from manure without the crust. Besides slowing ammonia loss, the hard crust on manure slurry also reduces methane emissions. Petersen and Ambus (2006) proved that methane-oxidizing bacteria exist in the hard crust of manure slurry, which oxidize methane into CO_2, thus achieving an emission reduction because methane is a more potent greenhouse gas than CO_2. When the concentration of methane is 500–50,000 ppmv, the amount of emission reduction by methane-oxidizing bacteria is 1–4.5 g $CH_4\,m^{-2}$ $days^{-1}$ (Petersen and Ambus 2006).

Permeable covers are less expensive than impermeable covers, but they do not last as long and are not as effective at reducing the emissions of odors and gases. However, they can provide reductions in odor, ammonia, and hydrogen sulfide emissions from manure storage facilities. A wide variety of organic and man-made materials have been utilized to construct permeable covers with variable results.

If impermeable covering materials are adopted, then the mass transfer between manure with the outside is cut off. Meanwhile, an anaerobic environment is created within the manure, promoting the generation of methane. Then gas collection devices can be installed to capture methane for cooking and heating purposes. In addition, the use of covering materials can effectively prevent the emission of nitrogen containing gases such as ammonia, thereby retaining nutrients in the manure. After a period of storage, it can be applied onto farmland as organic fertilizer.

13.1.7 Agro-forestry (Mitigation)

Agro-forestry is the production of livestock or food crops on land that also grows trees for timber, firewood, or other tree products. It includes shelterbelts and riparian zones/buffer strips with woody species. The standing stock of carbon aboveground is usually higher than the equivalent land use without trees, and planting trees may also increase soil carbon sequestration. But the effects on N_2O and CH_4 emissions are not well known.

Agro-forestry, as defined by the World Agroforestry Centre, is "a dynamic, ecologically based, natural resources management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic, and environmental benefits for land users at all levels." On the other hand, the Association for Temperate Agroforestry describes it as "an intensive land management system that optimizes the benefits from the biological interactions created when trees and/or shrubs are deliberately combined with crops and/or livestock" (IGUTEK 2011). Agro-forestry offers great potential for carbon sequestration (UNFCCC 2008).

Terrestrial sequestration is based on the fact that plants take CO_2 out of the atmosphere through photosynthesis and store it as organic carbon in aboveground biomass (trees and other plants) and in the soil through root growth and the incorporation of organic matter (Fig. 13.13). Thus, the process of carbon loss through land-use change can be reversed, at least partially, through improved land-use and management practices. In addition to afforestation, changes in

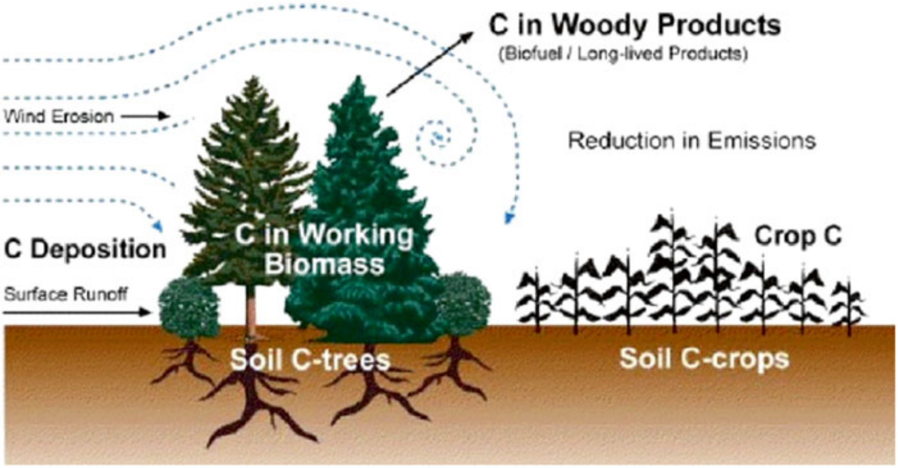

Fig. 13.13 Agro-forestry and carbon sequestration (Source: IGUTEK 2011)

agricultural land management, such as the adoption of tillage practices that reduce soil disturbance and incorporate crop residues into the soil, can remove carbon from the atmosphere and store it in the soil as long as those land-use and management practices are maintained. Agro-forestry systems will vary by region. However, crops and forests together will elevate the carbon conserving capacity of the agroecosystem of a region.

Agro-forestry is one of the important terrestrial carbon sequestration systems. It involves a mixture of trees, agricultural crops, and pastures to exploit the ecological and economic interaction of an agroecosystem. Agroecosystems play a central role in the global carbon cycle and contain approximately 12 % of world terrestrial carbon (Dixon 1995). Increased C sequestration by agro-forests is an important element of a comprehensive strategy to reduce GHG emissions. According to Richards and Stokes (2004), forest land can fix about 250 million metric tons of carbon each year (12 % of total CO_2 emissions), cropland can sequester about 4–11 % of atmospheric C/year, and grazing land can sequester about 5 % of atmospheric C/year in the USA. The system of planting trees in strategic locations on farms to compensate for the lost carbon due to cutting of trees for agriculture is called agro-forestry. It has the biggest potential for increasing agricultural carbon sequestration in tropical countries (Youkhana and Idol 2009).

Increasing agro-forestry may involve practices that increase emissions of GHGs including shifting cultivation, pasture maintenance by burning, paddy cultivation, N fertilization, and animal production. On the other hand, several studies have shown that including trees in agricultural landscapes often improves the productivity of systems while providing opportunities to create C sinks (Albrecht and Kandji 2003). The trees play various functions, including shading crops, erosion control, and nutrient cycling. Shading crops and the rhizosphere by the trees would significantly reduce evapotranspiration (ET) of the cropped area, although overall ET of crops plus trees may increase. The soil organic carbon content increases at the rate of 50 kg ha^{-1} $year^{-1}$ in the top 10 cm depth of an improved forestry plantation of *Cassia siamia* where the high rate of litter fall under Cassia (5–7 Mg ha^{-1} $year^{-1}$) helps to maintain high soil organic carbon content (Lal et al. 1998b).

Bamboo is an especially effective agro-forest sink of CO_2 with a C sequestration rate as high as 47 % amounting to 12–17 t $CO_2\,ha^{-1}$ $year^{-1}$. It also generates 35 % more oxygen than other timber species (Aggarwal 2007). Additionally, bamboo plantations generate income and provide a livelihood for forest-dependent people.

Degraded lands can be used for plantations of fast-growing clones of bamboo species up to an altitude of 1,800 m. Bamboo grows much faster than other trees with some species growing up to 150 ft in just 6 weeks, occasionally more than 4 ft per day. Bamboo is a pioneering plant that can also grow in over grazed soil using poor agricultural techniques (Aggarwal 2007).

13.1.7.1 Advantages

- Trees act as a buffer against storms to prevent crop destruction.
- Dryland forests apparently manage to sequester carbon by reducing respiration rates and growing rapidly in early spring to take advantage of temperatures most favorable for growth (Rotenberg and Yakir 2010).
- Trees send their roots considerably deeper than crops, thereby placing organic matter at deeper depths in the soil where tillage would not accelerate its decomposition and the release of CO_2. In some instances, trees have extracted water from deeper depths which has become redistributed at shallower depths with positive effects on the growth of understory plants. In other cases, negative effects have also been reported, so the phenomenon remains controversial (Prieto et al. 2012). While such redistributions could be ecologically important, allowing some species to survive that would otherwise perish, it is less clear that the amounts of water involved would enable significant increases in the yield of agronomic crops.
- Leaf litter generates compost and serves as mulch that reduces runoff from rainfall. It also slows soil water loss from evaporation into the atmosphere.
- Agro-forestry trees also improve land cover in agricultural fields in addition to providing carbon inputs (root biomass, litter, and pruning) to the soil. These often reduce soil erosion, which is a crucial process in soil carbon dynamics.
- Carbon sequestration continues beyond harvest if boles, stems, or branches are processed into durable products that do not decompose and release CO_2.
- An agro-forestry-induced microclimate improves quality and increases the yield of some crops, although it is difficult to provide an estimation of the yield increase (Ebeling and Yasue 2008).
- Increasing soil carbon greatly benefits agricultural productivity and sustainability.
- Cost of carbon sequestration through agro-forestry appears to be much lower than through other CO_2-mitigating options (Albrecht and Kandji 2003).

13.1.7.2 Disadvantages

- This technology involves a very slow process of marginal carbon conservation.
- Soil carbon increases only in drier sites and actually decreases in wetter sites of agro-forestry regions (Jackson et al. 2002). As a result, the net carbon balance was marginally positive for the dry sites but negative for the wet sites.
- Under dry environments, the tree crop competition for water usually results in low crop yields, which makes this technology unattractive for dryland farmers. Under dryland conditions, trees with their effective rooting systems take more water compared to crops with relatively less effective rooting systems, so the crops are more vulnerable to water stress with consequent lower yields (Schroeder 1995).
- Various species of damaging insects, pests, and diseases have been associated with dead or dying trees. These are a major threat to the development of agro-forestry in the tropics.
- Emissions of other greenhouse gases such as N_2O and CH_4 in the atmosphere may increase, which reduces overall mitigation potential.

Agro-forestry is practiced to some extent all over the world. It is especially used for crops that benefit from the quality improvements associated with shading. However, the other benefits, including carbon sequestration, are being more recognized, and agro-forestry appears to be growing in popularity.

Light is a limiting factor for crop production in agro-forestry system, and most crops yield less when shaded with higher plants. Therefore, unless the several advantages such as quality improvement and carbon sequestration can overcome the yield depression, agro-forestry is not likely to become widespread. In addition, most farmers have the equipment to accommodate only a few similar crops. Adapting to growing both small stature and large stature tree crops presents a greater challenge for them.

Takimoto et al. (2008) experimented with two types of agro-forestry systems (live fence and fodder bank) at the Segou region, Mali. The live fence treatment showed US $96 net present value (NPV), 1.53 benefit–cost ratio (BCR), and 25.5 % internal rate of return (IRR), while fodder bank project showed $159 NPV, 1.67 BCR, and 29.5 % IRR.

Promotion of agro-forestry can reduce the amount of carbon emitted to the atmosphere annually by 700,000 million tons. This can happen due to controlled grazing, fire management, use of fertilizers, improved cultivars, and revegetation of reclaimed lands.

According to Rotenberg and Yakir (2010), agro-forestry in semiarid regions can sequester as much carbon as forests in temperate regions. Every ton of carbon added to and stored in plants or soils removes 3.6 t of CO_2 from the atmosphere.

According to Lal et al. (1998a), a small agro-forestry enterprise following nutrient recapitalization had a cost of $87 per ton of carbon sequestered in Eastern African Highlands. Sudha et al. (2007) carried out a cost–benefit analysis of baseline (chilli crops – best alternative to agro-forestry and the dominant preplantation crop) and agro-forestry (Eucalyptus clones) scenarios in the Khammam district, India. Costs and benefits under both the scenarios can be seen in Table 13.9.

Table 13.9 Costs and benefits under baseline and project scenarios for the period 2006–2035 (Sudha et al. 2007)

	Baseline scenario[a]	Project scenario
Present value (PV) of cost (US$/ha)	297	108
PV of benefit (US$/ha)	423	235
Net present value (NPV) of benefit (US$/ha/year)	126	178
Benefit–cost ratio	1.42	2.18

Note: Present value (PV) is the value on a given date of a payment or series of payments made at other times, while net present value (NPV) of a time series is defined as the sum of the present values of the individual cash flows (both incoming and outgoing) of the same entity

[a] The best alternative to plantations (chilli crop) has been used for the baseline scenario

13.1.8 Land-Use Change

According to the IPCC (2007c), one of the most effective methods of reducing emissions is often to allow or encourage the reversion of cropland to another land cover, typically one similar to the native vegetation. Converting land to another land cover can occur over the entire land area (called “set-asides”) or in localized spots, such as grassed waterways, field margins, or shelterbelts. The introduction image all the way at the top is a small-scale illustration of a set-aside in which a piece of land is no longer cultivated and allowed to grow back to another land cover.

Land cover changes often increase carbon storage. For instance, the conversion of arable cropland to grassland typically results in the increase of soil carbon due to lower soil disturbances and reduced carbon removal in harvested products (IPCC 2007c). Moreover, due to reduced inputs by the farmer, grasslands may also have reduced N_2O emissions from lower nitrogen inputs. Similarly, converting drained croplands back to wetlands results in the rapid accumulation of soil carbon. Planting trees can also reduce emission. The IPCC (2007c) concludes that because land cover (or use) conversion comes at the expense of lost agricultural productivity, it is usually an option only on surplus agricultural land or on croplands of marginal productivity.

GHG emissions from land-use change, including deforestation in tropical areas, are around 17 % of total GHG emissions. In most countries they are associated with agricultural activities and exceed emissions from all other agricultural sources. A recently published review of the literature quantifying the impact of land-use changes

Table 13.10 Change in soil organic carbon (SOC) following land-use change (Guo and Gifford 2002)

Land use		Percent change in SOC
Before	After	
Pasture	Plantation	−10
Native forest	Plantation	−13
Native forest	Crop	−42
Pasture	Crop	−59
Native forest	Pasture	+8
Crop	Pasture	+19
Crop	Plantation	+18
Crop	Secondary forest	+53

on SOC analyzed the data following land-use changes from 74 publications (Table 13.10).

Wherever a land-use change decreased SOC (Table 13.10), for example, native forest to crop (−42 %), the reverse will increase SOC by a comparable but not equal amount. The totals and rates of change in SOC will depend on the soil type, texture and structure, precipitation, temperature, farming system, specific crops and trees grown, and land management. Rates of change ranges from 0 to 150 kg C/ha year^{-1} in dry and warm regions and 100–1,000 kg C/ha year^{-1} in humid and cool climates (Lal 2004). Providing environmental conditions remain similar, SOC content is likely to reach its maximum 5–20 years after adoption of beneficial SLM practices and remain constant.

13.1.9 Restoration of Degraded Lands

A variety of factors cause agricultural lands to become degraded: excessive disturbance, erosion, organic matter loss, salinization, acidification, drainage, or other processes that curtail productivity. Carbon storage within these soils can be partly restored by practices that reclaim productivity such as:

- Enabling revegetation, for instance, in the form of planting vegetation
- Improving fertility through nutrient amendments
- Applying organic substrates such as manures, biosolids, and composts
- Reducing tillage and retaining crop residues
- Conserving water (IPCC 2007c)

Degradation of lands can result in the emission of greenhouse gases. Through restoration of lands, these emissions can be reduced.

The sustainable land management (SLM) practices identified fundamentally restore degraded soils, increasing plant growth (whether arable crops, rangeland plants, or trees) and better enabling them to cope with the impacts of climate change, whether they are wetter, drier, or more variable conditions. They include:

- Revitalizing biological tillage
- Reducing compaction
- Increasing rainfall infiltration
- Protecting natural drainage through the soil profiles
- Increasing water storage capability
- Naturally improving soil nutrient status

Several possible benefits can be noted from the restoration of degraded lands and peatlands. First, restoring degraded lands and peatlands improves biodiversity. Second, peatlands purify water and can therefore be regarded as an important water supply source. Third, restored (peat) lands can be more effectively used as flood mitigation areas. Fourth, restored peatlands have been shown to significantly reduce fire risk (Peat Portal Assessment Report 2008). Finally, due to aesthetic quality of fully restored peatlands and other degraded lands, sustainable development can be supported through ecotourism activities.

Restoration of organic soils therefore has a variety of biodiversity and environmental co-benefits. However, the economic impact depends upon whether farmers receive payment for the GHG emission avoidance and reductions achieved. Market-based mechanisms might be able to support restoration of peatlands and degraded lands as they add carbon valuation. Restoration of degraded lands will provide higher yields and economic returns, less new cropland, and provide societal benefits via production stability.

13.1.10 Organic Agriculture

Organic farming restricts the use of artificial fertilizers and pesticides, and it promotes the use of crop rotations, green manures, compost, biological pest control, and mechanical cultivation for weed control. These measures use the natural environment to enhance agricultural productivity. Legumes are planted to fix nitrogen into soil, and natural insect predators are encouraged. Crops are rotated to renew soil, and natural materials such as potassium bicarbonate and mulches are used to control diseases and weeds. Crop diversity is a distinct feature of organic farming. However, organic farming originated as a small-scale enterprise with operations from under 1 acre (4,000 m^2) to under 100 acres (0.40 km^2). Crop rotation, cover cropping, reduced tillage, and application of compost are varieties of methods used in organic agriculture. Organic agriculture is one of the important options for carbon sequestration which can reduce greenhouse gases.

Organic farmers use several different techniques. The most effective ones are fertilization by animal manure, by composted harvest residues, and by leguminous plants such as (soil) cover and (nitrogen) catch crops. Introducing grass and clover into rotations for building up soil fertility, diversifying the crop sequences, and reducing plowing depth and frequency also augment soil fertility. All these techniques increase carbon sequestration rates in organic fields, whereas in conventional fields, soil organic matter is exposed to more tillage and consequent greater losses by mineralization. The annual sequestration rate increases up to 3.2 t of CO_2 ha^{-1} $year^{-1}$ by organic farming (Smith et al. 2007).

Historically, agriculture was organic, relying on the recycling of farm wastes and manures. Very little or negligible amounts of external inputs were applied. Sustainable farming practices and cycles evolved over centuries, integrated with livestock rearing. For instance, farmers of ancient India are known to have evolved nature-friendly farming techniques and practices such as mixed cropping and crop rotation.

Besides overcoming a tradition of recently adopted synthetic fertilizers and pesticides, the primary barriers to adoption of organic farming are the lower productivity and consequently higher prices, as well as lower produce quality in the market place. Greater education of farmers and the public needs to be done to show that the environmental and long-term sustainability advantages of organic agriculture are worth to the added current costs.

13.1.10.1 Advantages

- Organic agriculture aims to improve soil fertility and N supply by using leguminous crops, crop residues, and cover crops to eliminate fossil fuel used to manufacture N fertilizer. The addition of the crop residues and cover crops leads to the stabilization of soil organic matter at higher levels and increases the sequestration of CO_2 into soils.
- Organic agriculture increases soil's water retention capacity, which would enable a crop to go longer into a drought cycle assuming an initial full profile. This should provide an adaptation to unpredictable climatic conditions. Soil C retention is more likely to withstand climatic challenges and soil erosion, an important source of CO_2 losses.
- Organic agriculture can contribute to agroforestry production systems, which offer additional means to sequester carbon.
- Organic systems are highly adaptive to climate change due to the application of traditional skills and farmers' knowledge, soil fertility-building techniques, and a high degree of diversity.
- Organic agriculture as a water protector reduces water pollution due to the absence of pesticides and chemical fertilizers.
- Organic agriculture is compatible with conservation tillage, thereby enabling even greater C sequestration potential by incorporating this mitigation technology.

13.1.10.2 Disadvantages

- Organic agriculture is less productive compared to intensive conventional agriculture. Consequently, the yield of highly demanding crops such as potatoes, grapefruits, and horticultural crops is too low, and energy input

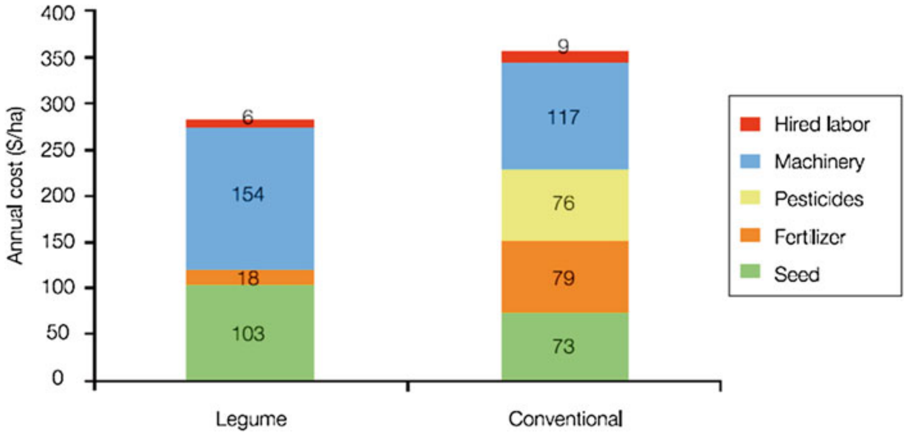

Fig. 13.14 Annual input costs for the legume and conventional grain rotations (Kimble et al. 2007)

becomes relatively more on per unit of crop production bases (Smith et al. 2007).

- Quality of organic-grown produce is often lower due to insect damage, which is less in conventional agriculture with its use of pesticides.
- Highly dependent on nutrients derived from livestock

Organic agriculture requires 28–32 % less energy compared to conventional systems. Input costs for seed, fertilizer, pesticides, machinery, and hired labor are approximately 20 % lower in a rotation that includes a legume compared with a conventional rotation system (Fig. 13.14) (Kimble et al. 2007).

In the Eastern African Highlands, animal manure application leads to 2,820 kg ha^{-1} year^{-1} carbon inputs with $156 per ha cost and 5.5 % carbon sequestration efficiency (Woomer et al. 1998). The sequestration of one ton of soil carbon using cattle manure requires $260, but return will increase by $1,066 (4.1 return ratio) as a result of the addition. Some experts estimate the cost of manure to be around $1,000, in which case the additional returns would almost vanish. Maize stover leads to 1,830 kg ha^{-1} year^{-1} carbon inputs with $37 per ha cost and 5.4 % carbon sequestration efficiency. The sequestration of one ton of soil carbon using maize stover requires $374, but this application also suppresses crop yields resulting in a loss of $112 (−1.3 return ratio).

Annual global sequestration potential of organic agriculture amounts to 2.4–4.0 Gt CO_2e year^{-1}, and it can be improved to 6.5–11.7 Gt CO_2e year^{-1} by using new technologies in organic agriculture (Smith et al. 2008).

Organic agriculture has lower methane and nitrous oxide emissions of 0.6–0.7 Gt CO_2e year^{-1} in comparison to conventional agriculture, which includes the burning of crop residue (Smith et al. 2007). Organic agriculture has a significant potential to provide on-farm energy by biogas production from slurry and compost, although this would detract from the quantities of organic material to return to the soil.

If all agricultures were organic, the elimination of nitrogen fertilizers would save substantial emissions. For example, in the case of UK, 1.5 % of national energy consumption and 1 % of national greenhouse gas emissions would be saved (Mae-Wan Ho and Lim Li Ching 2008). Earlier studies showed that GHG emissions would be 48–66 % lower per hectare in organic farming systems in Europe. The lower emissions were attributed to zero input of chemical N fertilizers, less use of high energy-consuming feedstock, low input of P (phosphorus) and K (potassium) mineral fertilizers, and elimination of pesticides. However, the productivity likely would be lower.

Although not limited to organic farming, the use of N from manure and compost or fixed from the air by leguminous plants has a mitigation potential that amounts to 4.5–6.5 Gt CO_2e year^{-1} (out of 50 Gt CO_2e year^{-1} global GHG emissions) or about 9–13 % of the total GHG emissions. The mitigation is accomplished by sequestering C in soils due to intensive humus production (Smith et al. 2007). Regular applications of livestock manure can induce substantial increases in soil organic carbon over the course of a few years (Lal et al. 1998b). Organic agriculture has lower N_2O emissions, i.e., 1.2–1.6 Gt CO_2e year^{-1}. In organic agriculture, biomass is not burned. It reduces the N_2O emissions by 0.6–0.7 Gt CO_2e year^{-1} in comparison to conventional agriculture (Smith et al. 2007). Organic systems are highly adaptive to climate change due to:

- Application of traditional skills and farmers' knowledge
- Soil fertility-building techniques
- High degree of diversity

Organic farming could considerably reduce the GHG emissions of the agriculture sector and make agriculture almost GHG neutral (Niggli et al. 2009). Greenhouse gas emissions due to the applications of synthetic fertilizers are estimated to be 1,000 million tons annually. These emissions would not occur using an organic approach. GHG emissions of agriculture would be reduced by roughly 20 %. Another 40 % of the GHG emissions of agriculture could be mitigated by sequestering carbon into soils at rates of 100 kg of C ha^{-1} year^{-1} for pastureland and 200 kg of C ha^{-1} year^{-1} for arable crops. By combining organic farming with reduced tillage, the sequestration rate can be increased to 500 kg of C ha^{-1} year^{-1} in arable crops as compared to plowed conventional cropping systems, but as the soil C dynamics reach a new equilibrium, these rates will decline in the future. This would reduce GHG emissions by another 20 %. Organic farming is an important option in a multifunctional approach to climate change.

13.2 Livestock Management

Ruminant animals have a unique digestive system. Ruminants possess a rumen, or large fore-stomach, in which microbial fermentation breaks down coarse plant material for digestion. Nonruminant domesticated animals (e.g., swine, horses, mules) also produce CH_4 emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine, where the capacity to produce CH_4 is lower (USEPA 2005). Enteric fermentation enables ruminants to eat plant materials but also produces CH_4, a potent greenhouse gas that contributes to global climate change. During digestion, microbes present in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process is referred to as enteric fermentation and produces CH_4 as a by-product, which can be exhaled or eructated by the animal. The amount of CH_4 produced and excreted by an animal depends primarily on the animal's digestive system and the amount and type of feed it consumes. In fact, with an emission of approximately 140.8 Tg CO_2eq in 2008, enteric fermentation accounts for about 2 % of the total US emissions in 2008 (EPA 2010)

In Table 13.11, the enteric fermentation emissions within the USA are displayed per livestock type. In the USA, beef cattle are by far the largest

Table 13.11 CH_4 emissions from enteric fermentation per livestock type (EPA 2010)

	CH_4 emissions from enteric fermentation per livestock type (Tg CO_2 eq.)				
Livestock type	1990	1995	2000	2005	2008
Beef cattle	94.5	107.7	100.6	99.3	100.8
Dairy cattle	32.0	30.5	30.9	30.6	33.1
Horses	1.9	1.9	2.0	3.5	3.6
Swine	1.7	1.9	1.9	1.9	2.1
Sheep	1.9	1.5	1.2	1.0	1.0
Goats	0.3	0.2	0.3	0.3	0.3
Total	**132.4**	**143.7**	**136.8**	**136.7**	**140.8**

contributor of methane emissions, accounting for 72 % in 2008. Dairy cattle accounted for 23 % in 2008, with the remainder of emissions arising from horses, sheep, swine, and goats (EPA 2010).

Clearly, livestock are important sources of methane. In fact, the US EPA calculated that livestock, especially ruminants such as cattle and sheep, account for approximately one-third of global anthropogenic emissions of CH_4 (US EPA 2006). Enteric CH_4 emissions from livestock are estimated to be the second largest source of global agricultural non-CO_2 (IPCC 2007a, b, c). In addition, N_2O emissions are generated by livestock through secretion of nitrogen through the urine and feces. As such, it is important to address CH_4 emissions from livestock.

13.2.1 Feed Optimization

The amount of CH_4 emissions is mainly affected by the feed type, feed intake, ambient temperature, rate of consumption of feed, balance of nutrients in the feed for microbial growth, and balance of microorganisms that develop (bacteria, protozoa, and fungi) which largely depend on the chemical composition of diet (Ding 2007).

The diet of ruminant animals (mainly cattle, sheep, buffalo, camels, etc.) is primarily made up of forage and concentrate. Forage mainly refers to grass or hay with crude fiber content over 18 %, most commonly including corn straw, alfalfa, and silage. Forage provides the animals with crude fiber, which plays an essential role in maintaining normal rumen fermentation, providing body energy and sustaining normal microbial flora, as well as promoting the synthesis of milk fat by the milk cow. At the same time, concentrates mainly supply the animals with protein, fat, minerals, and vitamins. Therefore, both forage and concentrate are necessary for ruminant animals. Moreover, the ratio of concentrate to forage in diet will substantially affect the ruminant animal's growth performance, rumen's fermentation function, methane emission, and health condition.

Generally, when the proportion of forage feed is larger, the cellulolytic bacteria proliferate, and acetic acid fermentation is the dominant fermentation type in rumen with a large amount of hydrogen produced. As a consequence, partial pressure of hydrogen increases, which stimulates the massive proliferation of methanogens, with an increase in methane emissions. When soluble carbohydrates or starch are fed, i.e., the proportion of dietary concentrate increases, then rumen pH values decline, thereby inhibiting the propagation of methanogens and ciliates, while increasing propionic acid production (Demeyer 1967). Since propionic acid fermentation consumes hydrogen, which reduces the raw materials needed for CH_4 formation, CH_4 emissions are lowered. An appropriate increase of the proportion of concentrate in the ruminant animals' diet can increase the proportion of propionic acid in rumen, while reducing the content of acetic acid, and improving feed utilization efficiency and production performance of animals. Propionic acid is mainly converted into body composition by the liver, and then it provides energy for breeding, growth, milk production, and meat production. CH_4 emissions and propionic acid production are negatively correlated (Church 1988). Hence, controlling the concentrate and forage ration can not only reduce the amount of CH_4 emitted but also improves the production performance of ruminant animals.

There are constraints in promoting CH_4 emission reductions by changing the proportion of fine feed to forage feed in daily diet. First, the concentrate to forage ratio in daily diet refers to the proportion of the dry matter contained, and the actual feed intake of animals may not be consistent with the calculated proportion. Secondly, cornstalks are not palatable to animals, so the ammonia treatment or silage process is necessary, and there should be a process of adoption. Thirdly, CH_4 emissions may increase if the proportion of dietary concentrate is out of suitable range (40–50 %) (Sun et al. 2008). Furthermore, farm management sees no direct benefits in CH_4 reduction. There is therefore a need to explore new financial mechanisms under climate conventions to encourage the application of feed optimization for reducing the CH_4 emissions.

The production of CH_4 during rumen fermentation is a necessary by-product, which cannot be completely eliminated. The control of concentrate to forage ratio in ruminant animals' daily diet to reduce CH_4 emissions has certain advantages and disadvantages.

13.2.1.1 Improved Feeding Practices

An animal's feed quality and feed intake affect CH_4 emissions. In general, lower feed quality or higher feed intake lead to higher CH_4 emissions. Feed intake is positively related to animal size, growth rate, and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types, as well as among different management practices for individual animal types.

Because CH_4 emissions represent an economic loss to the farmer, where feed is converted to CH_4 rather than to product output, viable mitigation options can entail feed efficiency improvements to reduce CH_4 emissions per unit of beef or milk (IPCC 2007a, b, c). However, these mitigation options can actually increase CH_4 per animal.

Through replacing forages with the feeding of more concentrates, methane emissions can be reduced (Lovett et al. 2003). While the concentrates may increase the daily methane emissions per animal, the emissions per kg of feed intake and per kg of product are reduced. The extent of reduced emissions per kg of feed intake or per kg of product decreases as production increases (IPCC 2007a, b, c). Feeding concentrates' benefits depend on whether the number of animals can be reduced or whether slaughter age can be reduced. In addition, it is important to consider how the practice affects land use, the nitrogen content in the manure, and the emissions from transporting and producing the concentrates in the first place (Lovett et al. 2006; IPCC 2007a, b, c).

Other practices to reduce methane emissions are available. Adding certain oils or oilseeds to the diet, improving pasture quality, and optimizing protein intake to reduce nitrogen excretion and N_2O emissions are examples (IPCC 2007a, b, c).

13.2.1.2 Specific Agents and Dietary Additives

Adding agents and/or dietary additives can also reduce CH_4 emissions. Most of these agents or additives aim at suppressing methanogenesis which is the chemical process that creates methane. A wide range of these agents or additives have been proposed to reduce CH_4 emissions:

- Ionophores are antibiotics that can reduce CH_4 emissions, but their effect may be transitory and they have been banned in the European Union.
- Halogenated compounds inhibit the growth of methanogenic bacteria (the bacteria that produce the CH_4), but their effects can also be transitory and they can have side effects such as reduced intake.
- Adding plant compounds (condensed tannins, saponins, or essential oils) can also reduce CH_4 emissions. However, adding such compounds may have the negative side effect of reduced digestibility of the diet.
- Probiotics have shown to result in small and insignificant effects. However, selecting strains specifically for CH_4-reducing ability might be able to improve results.
- Propionate precursors such as fumarate or malate reduce CH_4 formation. These precursors reduce CH_4 by acting as alternative hydrogen acceptors. However, this option is expensive due to the requirement for high doses of precursors to elicit effect.
- Hormonal growth implants do not specifically reduce CH_4 emissions by themselves, but by improving animal performance, they can reduce emissions per kg of animal product.
- Vaccines against methanogenic bacteria are being developed but are not yet available commercially.

13.2.1.3 Advantages

1. There is no additional cost of CH_4 reduction.
2. CH_4 reduction and improvement of productivity could be consistently realized.
3. The technology could be applied in any animal production system by using feed optimization.

13.2.1.4 Disadvantages

1. Improper ratio of concentrate to forage feed may result in abnormal rumen fermentation and increase of CH_4 production.
2. The technician is required to produce the best possible results of feed optimization.
3. Monitoring the characteristics of the forage and concentrate is required.

The regression relationship between 4 % fat corrected milk (FCM), yield (Y), and grain supply (X) has the equation $Y = 1.962X + 3.492$. This indicates that with every additional 1 kg of grain feed intake, the milk production could increase by 2 kg. The methane production for each kg of milk decreases with the increase of the proportion of dietary concentrate.

There are considerable potentials to improve animal production performance such as yield per unit and to reduce methane emissions by using feed optimization techniques. Many experimental tests have shown that with the improvement of feeding technology, CH_4 emission per unit of livestock is reduced (Na 2010).

It is reported that when daily milk production increases from 25 to 30 kg, then the CH_4 emissions per unit milk product decreases by 10 % (Yang 2000). When the average daily gain increases from 0.65 to 0.80 kg, the CH_4 emitted per unit of weight gain can be reduced by 14 %. According to the Na (2010) studies, when milk yield of milk cow increases from 11 to 13 kg, the CH_4 emission per unit of milk product decreases by around 39 %.

The regression relationship between CH_4 production per unit of FCM and grain supply was expressed as $Y = -2.546X + 46.442$. This also indicates that with every additional 1 kg of cereal feed intake, the CH_4 emission per kg of FCM can be reduced by about 2.5 l.

13.2.2 Genetically Modified Rumen Bacteria

To optimize the synthetic or metabolic pathway of microorganisms related to CH_4 synthesis is by employing modern molecular biotechnology to obtain genetically modified microorganisms. Then the genetically modified microorganisms are introduced back into the rumen ecosystem to establish a relatively stable microbiota that can replace or compete with the original pathway of methanogenesis to reduce CH_4 synthesis in the rumen.

Most CH_4 emissions from ruminants are synthesized by methanogenic archaea in rumen. The methanogens mainly use carbon dioxide and hydrogen to synthesize CH_4. Protozoa and other microbes involved in cellulose-degrading or glucose-metabolic pathways provide carbon dioxide and hydrogen and other mono carbon compounds necessary for methanogens. Therefore, the process of CH_4 synthesis is implicated with complex symbiotic relationships of ruminal microbes, and improper manipulation may break metabolic homeostasis in rumen. However, the development of modern molecular biotechnology and gene engineering technology provides a great opportunity for the improvement of rumen microbiota to bring about optimal reduction in CH_4 emissions.

With respect to the process of feed degradation and CH_4 synthesis, there are some possible links in realizing the CH_4-mitigating goal with the application of developing genetically modified microorganisms. First, digestibility is one of the important factors influencing CH_4 synthesis in the rumen. Cellulose, semi-cellulose, and lignin contents are high in forage, and they are difficult to degrade completely, and therefore they are positively associated with CH_4 emissions. Based on mutagenic breeding methods and transgenic technology, high-efficiency exogenous genes could be introduced into microbial genomes and then express high-efficiency degrading enzymes in rumen. As a consequence, the cellulose decomposition bacteria are strengthened to better degrade refractory carbon structure in forage, thus resulting in high-efficient feed digestibility and energy use. Since more energy is obtained from an equal quantity of feed and animal production is improved, CH_4 emission per unit of product could be reduced.

The reaction of carbon dioxide and hydrogen to form CH_4 is a key step to decrease the hydrogen partial pressure in the rumen, so finding new hydrogen competitor or CH_4 oxidative pathway could reduce CH_4 production. For example, acetogens can also utilize hydrogen as substrate and have been found to be dominant in kangaroos' rumen. If acetogens that can outcompete methanogens in hydrogen intake are selected by genetically modified technology and then form stable microflora in rumen, less CH_4 would be produced from ruminants. CH_4 oxidation may be another possible solution to solve this problem. Methanotrophic bacteria can oxidize CH_4 to carbon dioxide, and they inhabit widely diverse environments. Through genetic modification, bacteria with high CH_4-oxidative efficiency can be obtained. Once these bacteria are introduced into rumen and form stable microflora, CH_4 will be used to form carbon dioxide without affecting ruminal fermentation.

At present, the researchers worldwide engaging in CH_4 emission mitigation of ruminants mainly focus on nutrition regulation, optimization of feed formula, and application of additives. In comparison, the CH_4 mitigation in ruminants using genetic modification is only just now being investigated. This technology, marked by complexity of operation, excessively high up-front investment, and long period of study, requires multidisciplinary cooperation. All these factors together restrict the development of genetic modification of microorganisms to reduce CH_4 emissions.

13.2.2.1 Advantages

- Improving digestibility, fermentation, energy utilization efficiency of feed, and animal performance.
- Methanogens and other microorganisms form symbiotic relationships and benefit mutually (Joblin et al. 1989), so introducing genetically modified microbes favors the homeostasis of microbial diversity and complexity of symbiotic relationship in rumen, avoiding side effects on rumen ecosystems.
- Many approaches for reducing CH_4 emissions have been tried, including research on feed preparation, vaccines, and additives (Yvette et al. 2009). However, these approaches lack sustainability and heritability. In comparison, once the genetically modified microbes survive in rumen, they will be carried by ruminants as long as they live and can be inherited by their offspring, without any extra costs to maintain CH_4 mitigation.
- Although chemical inhibitors or antibiotics can reduce CH_4 synthesis, the long-term adoption may cause residues of organic matter or antibiotics in meat and milk and bad health conditions of animals. However, genetic modification of microorganisms in rumen can eliminate all the adverse effects mentioned above and achieve CH_4 emission reduction on the premise that food security is guaranteed.

13.2.2.2 Disadvantages

In spite of the advantages of genetic modification of rumen microorganisms in reducing CH_4 emissions in rumen, several problems and technical barriers remain.

- Most of the microorganisms in rumen are hard to isolate or culture. Mutagenic screening and genetic modification require more information on the mechanism and ecological functions of microbial metabolism and are still at a trial stage.
- Relevant reports indicate that technical barriers exist for introducing genetically modified strains into the rumen ecosystem, as well as for establishing a stable microflora and a stable symbiotic relationship (Cotta et al. 1997).

Genetic modification of rumen organisms is a system engineering problem involving nutrition, molecular biology, physiology, genetics, microbiology, biological chemistry, and so on. Though this field has just started, the perspective of CH_4 mitigation in ruminants has been highlighted by this technology. Since the research on genetic modification of rumen microorganisms is based on the principles of genetics, this modification is, in theory, supposed to be inheritable, which is the greatest advantage of this technology. Once this technology can be put into actual application, ruminants will not only reduce CH_4 emissions but also be capable of passing their ability in CH_4 reduction to their offspring, permanently.

Compared to others, this technology could change the rumen CH_4 problem once and for all, in theory. If this is so, it would remarkably reduce production costs and achieve considerable economic benefits because no more extra expense would be required to maintain long-term CH_4 mitigation.

13.2.3 Straw Ammonization and Silage

13.2.3.1 Straw Ammonization

Straw ammonization is a process by which low-value forage such as cornstalks, rice straw, wheat straw, and straw of other crops is ammoniated. Adding liquid ammonia, urea, or ammonium bicarbonate as ammonia sources result in the straw lignin being completely degraded, while the nutrients are enhanced. It is made more easily digestible by rumen microorganisms, which increases the digestibility of forage (Fig. 13.15).

The cellulose part of the straw can be digested and utilized by ruminant animals, while the lignin part cannot be digested. The main function of ammonization is to generate ammonolysis reaction using ammonia and straw, by damaging the ester bonds between lignin and polysaccharide, so that it can contact with digestive enzymes more easily, with an improvement in digestibility of straw. The digestibility and feed intake of ammoniated straw can be increased by approximately 20 %, and the content of crude protein in ammoniated straw can be increased by two to three times (Guo 1996).

(i) *Advantages*
  - Saving grain and reducing the dependence of animal husbandry on grain.
  - Improving palatability and the feed intake of forage by livestock.
  - Increasing the digestibility of organic matters in forage by 10–12 % and doubling the content of crude protein.
  - The materials are easily accessed with simple methods.
  - Reducing feeding costs and increasing economic benefits.

(ii) *Disadvantage*
  - The ammonia utilization efficiency is as low as approximately 50 %. The surplus ammonia is discharged into the environment after the ammonization facilities are opened, which causes environmental pollution and threatens the health of animals and human beings.

13.2.3.2 Straw Silage

Straw silage refers to forage that is prepared through the fermentation of chopped fresh green fodder, forage grass, and all kinds of vines and other materials by lactobacillus in the anaerobic conditions of an airproof silage container (tower or silo).

To make straw silage, fresh plants are tightly packed in the airtight container, and the sugar contained in the raw materials is converted into organic acids (mainly lactic acid) via the anaerobic fermentation of microorganisms (mainly

Fig. 13.15 Process of straw ammonization (Source: hbav.gov.cn)

lactobacillus). When the lactic acid in the silage material reaches a certain concentration (pH lower than 4.2), the activities of other microorganisms are inhibited, and the nutrients in the materials are prevented from being broken down or destroyed by microorganisms. For this reason the nutrients in the forage can be retained. A great deal of heat is produced during the process of lactic fermentation. When the temperature of silage material rises to 50 °C, the activities of lactobacillus stop, and the fermentation is over. As the forage for silage is stored under airtight conditions with no microbial activities, it can remain unchanged for a long time.

(i) *Advantages*

- Minimal loss of nutrients (generally by less than 10 %) and effectively maintains the freshness of green feed.
- Fragrant, soft, and juicy and, therefore, highly palatable to livestock.
- Expands the application scope of feed sources.
- Easy to store in large quantities for a long time, as an economical and safe approach for silage.
- Less restricted by climate and season during storage.
- The preparation process of silage can kill pathogenic insects, weed seeds, etc.
- Improved feed digestibility and reduced methane emissions.

(ii) *Disadvantages*

- The straw silage production process needs to be done quickly.
- The high degree of mechanization requires a high investment cost.

Straw ammonization and silage can significantly improve the digestibility of forage. One experiment indicated that the feed intake was increased by 53 and 32.8 %. In addition, the average daily weight gain was increased by 126 and 97.4 % by feeding the beef cattle with ammoniated straw and silage, respectively, than those by feeding dry cornstalks (Wang Jinli et al. 2008).

The investment in straw ammonization and silage technology is concentrated on expenses in construction of storage facilities, machinery, and covers. More economic benefits are reaped mainly by increasing daily weight gain and milk yield of animals fed with treated forage. Wang Jinli et al. (2008) showed through the experiment of beef cattle with cornstalks conducted with different treatment methods that the cost of coarse feed per head of cow increased by 45.5 % and 51.6 % with the use of ammoniated straw and silage, respectively. However, the corresponding revenues increased by 153 and 68.8 %. The research result by Li Wen-bin et al. (2010) showed that the profit of breeding beef cattle with silage increased by 51.5 % more than that with dry cornstalks. It can be concluded that considerable economic benefits are achieved by feeding animals with ammoniated straw and straw silage.

CH_4 emissions of ruminant animals are produced through the normal fermentation of the feed taken by animals in the digestive tract. The energy loss in the form of CH_4 by ruminant animals accounts for about 2–15 % of the total energy intake (IPCC 2000). Generally, the amount of CH_4 emissions by a single animal increases with the weight of the animal. Higher level of CH_4 emission are observed under the greater feed intake and with lower feed digestibility. Therefore, the improvement of feed quality and animal productivity is an effective approach to reduce CH_4 emissions of ruminant animals (Dong et al. 2008).

Dong et al. (2008) calculated and compared CH_4 emissions of ruminant animals after the straw was treated with ammonization and silage technology using the IPCC method. The results showed that the CH_4 emissions were reduced by 16–30 % by feeding treated straw than by feeding dry straw. CH_4 emissions of beef cattle that were fed dry cornstalks and cornstalk silage were 229 L/d and 196 L/d, respectively, under the conditions of identical energy intake level and the same ratio of fine feed to coarse feed; the CH_4 emissions of the silage were reduced by 14.4 % compared to the dry stalk (Fan et al. 2006).

Na Renhua et al. (2010) showed that corn straw after treatment of silage technology can help improve feed digestibility and reduce CH_4 production through in vitro digestion test; with identical ratio of fine feed to coarse feed, the CH_4 emission was decreased by 30 % by feeding silage than by feeding dry corn. In China, the proportion of silage and ammoniated straw feeding is only 44 % at present. Feed saving, improvement of feed conversion efficiency, and reduction in CH_4 emission can all be achieved by constantly increasing the proportion of silage to ammoniated straw. The potential for CH_4 emission reductions is also tremendous.

13.2.4 Grazing Land Management

Grazing lands occupy much larger areas than croplands (FAOSTAT 2006) and are usually managed less intensively. Several management techniques can be identified that will support climate change mitigation efforts:

- Grazing intensity management
- Increased productivity
- Nutrient management
- Fire management
- Species introduction

The total mitigation potential of grazing land management techniques is substantial.

13.2.4.1 Grazing Intensity

The intensity and timing of grazing can influence the removal, growth, carbon allocation, and flora of grasslands, thereby affecting the amount of carbon accrual in soils (Conant et al. 2001, 2005). Carbon accrual on optimally grazed lands is often greater than on ungrazed or overgrazed lands (Liebig et al. 2005). The effects are inconsistent, however, owing to the many types of grazing practices employed and the diversity of plant species, soils, and climates involved (Derner et al. 2006). The influence of grazing intensity on emission of non-CO_2 gases is not well-established, apart from the direct effects on emissions from adjustments in livestock numbers.

13.2.4.2 Increased Productivity (Including Fertilization)

As for croplands, carbon storage in grazing lands can be improved by a variety of measures that promote productivity. For instance, alleviating nutrient deficiencies by fertilizer or organic amendments increases plant litter returns and, hence, soil carbon storage (Conant et al. 2001). Adding nitrogen, however, often stimulates N_2O emissions (Conant et al. 2005) thereby offsetting some of the benefits. Irrigating grasslands, similarly, can promote soil carbon gains (Conant et al. 2001). The net effect of this practice, however, depends also on emissions from energy use and other activities on the irrigated land (Schlesinger 1999).

13.2.4.3 Nutrient Management

Practices that tailor nutrient additions to plant uptake, such as those described for croplands, can reduce N_2O emissions (Dalal et al. 2003). Management of nutrients on grazing lands, however, may be complicated by deposition of feces and urine from livestock, which are not as easily controlled nor as uniformly applied as nutritive amendments in croplands (Oenema et al. 2005).

13.2.4.4 Fire Management

On-site biomass burning (not to be confused with bioenergy, where biomass is combusted off-site for energy) contributes to climate change in several ways. Firstly, it releases GHGs, notably CH_4 and, and to a lesser extent, N_2O (the CO_2 released is of recent origin, is absorbed by vegetative regrowth, and is usually not included in GHG inventories). Secondly, it generates hydrocarbon and reactive nitrogen emissions, which react to form tropospheric ozone, a powerful GHG. Thirdly, fires produce a range of smoke aerosols which can have either warming or cooling effects on the atmosphere; the net effect is thought to be positive radiative forcing (Venkataraman et al. 2005). Fourth, fire reduces the albedo of the land surface for several weeks, causing warming (Beringer et al. 2003). Finally, burning can affect the proportion of woody versus grass cover, notably in savannahs, which occupy about an eighth of the global land surface. Reducing the frequency or intensity of fires typically leads to increased tree and shrub cover, resulting in a CO_2 sink in soil and biomass (Scholes and van der Merwe 1996). This woody plant encroachment mechanism saturates over 20–50 years, whereas avoided CH_4 and N_2O emissions continue as long as fires are suppressed.

Mitigation actions involve reducing the frequency or extent of fires through more effective fire suppression, reducing the fuel load by vegetation management, and burning at a time of year when less CH_4 and N_2O are emitted (Korontzi et al. 2003). Although most agricultural-zone fires are ignited by humans, there is evidence that the area burned is ultimately under climatic control (Van Wilgen et al. 2004). In the absence of human ignition, the fire-prone ecosystems would still burn as a result of climatic factors.

13.2.4.5 Species Introduction

Introducing grass species with higher productivity, or carbon allocation to deeper roots, has been shown to increase soil carbon. For example, establishing deep-rooted grasses in savannahs has been reported to yield very high rates of carbon accrual (Fisher et al. 1994), although the applicability of these results has not been widely confirmed (Conant et al. 2001). However, it is very important to consider the ecological impacts of species introduction.

In the Brazilian Savannah (Cerrado Biome), integrated crop–livestock systems using Brachiaria grasses and zero-tillage are being adopted (Machado and Freitas 2004). Introducing legumes into grazing lands can promote soil carbon storage (Soussana et al. 2004), through enhanced productivity from the associated N inputs, and perhaps also reduced emissions from fertilizer manufacture if biological N_2 fixation displaces applied fertilizer N (Diekow et al. 2005).

13.2.5 Longer-Term Management Changes and Animal Breeding

Productivity increases through better management and breeding practices often reduces methane emissions per kg of animal product (Boadi et al. 2004). However, directly selecting cattle for reduced methane production is still impractical due to difficulties in accurately measuring methane emissions (IPCC 2007a, b, c).

Through improved efficiency, meat-producing animals reach slaughter weight at a younger age. Therefore, lifetime emissions are reduced (Lovett and O'Mara 2002). However, emissions over the whole system may not always decrease as the result of such practices. For example, intensive selection for higher yield in dairy cattle may reduce fertility. The reduced fertility requires more replacement heifers in the herd which increases whole system emissions (Lovett et al. 2006).

Table 13.12 summarizes the techniques available for methane mitigation in livestock management.

13.3 Energy Management

13.3.1 Agriculture for Biofuel Production

Biomass from the agriculture sector can be used to produce biofuels – solid, liquid, and gaseous. Biofuels substitute fossil fuels for energy delivery. If biomass is grown in a sustainable cycle to produce biofuels, such agriculture practices mitigate GHG emissions due to fossil fuel not being combusted. Biofuels can be derived from biomass sources such as corn, sugarcane, sorghum, soybean, crop residues, oil palm (*Elaeis guineensis*), switch grass, *Miscanthus*, bioengineered algae, and *Jatropha curcas* seeds, trees, and grasses. First-generation biofuel crops (such as sugarcane and maize) from which sap or grain ethanol are obtained are already being used. In addition, second-generation cellulosic ethanol crops (e.g., *Miscanthus*) appear promising.

Agricultural crops and residues are the major sources of feedstocks for energy to displace fossil fuels. A wide range of materials such as grain, crop residue, and cellulosic crops (e.g., switch grass, sugarcane, and various tree species) are used for the production of biofuel (Eidman 2005). These products are processed further to generate liquid fuels such as ethanol or diesel fuel (Richter 2004). These fuels release CO_2 when burned, but this CO_2 is of recent atmospheric origin (via photosynthesis) and displaces CO_2 which otherwise would have come from fossil carbon. The net benefit to atmospheric CO_2, however, depends on

Table 13.12 Summary of mitigation options available

Mitigation option	Description	Greenhouse gas effects
Improved feed conversion	Increase the amount of grain fed to livestock to increase the proportion of feed energy being converted to milk, meat, or work instead of animal maintenance. This option tends to increase emissions per animal but reduce emissions per unit output. It is more effective in reducing emissions per unit of production in regions where baseline feed is of relatively low quality. This option is applied to both beef and dairy cattle in all regions, although it was excluded from the MACs for some developed regions where it resulted in slightly higher GHG emissions	CH_4 and some N_2O
Antibiotics	Administer antibiotics (e.g., monensin) to beef cattle to promote faster weight gain, which reduces time to maturity and CH_4 production per kg of weight gain. This option is applied in all regions	CH_4 and some NO_2
Bovine somatotropin (bST)	Administer bST to dairy cattle to increase milk production. In many cases, this option increases CH_4 emissions per animal but typically increases milk production sufficiently to lower emissions per kg of milk. Because of opposition to the use of bST in many countries, this option was only applied in selected countries that currently approve of the use of bST or are likely to approve its use by 2010	CH_4 and some N_2O
Propionate precursors	Involves administering propionate precursors to animals on a daily basis. Hydrogen produced in the rumen through fermentation can react to produce either CH_4 or propionate. By adding propionate precursors to animal feed, more hydrogen is used to produce propionate and less CH_4 is produced. This option is applied to both beef and dairy cattle in all regions	CH_4 and some N_2O
Antimethanogen	Vaccine is developed by Commonwealth Scientific and Industrial Research Organization (CSIRO) that can be administered to animals and will suppress CH_4 production in the rumen. This option is applied to beef and dairy cattle, sheep, and goats in all regions	CH_4 and some N_2O
Intensive grazing	Moving to a more management-intensive grazing system where cattle are frequently rotated between pastures to allow recently grazed pastures time to regrow and to provide cattle with more nutritious pasture grazing that will permit replacement of more feed grains. This option may actually reduce animal yields but will decrease emissions by an even larger percentage. This option is applied to beef and dairy cattle in developed regions and Latin America	CH_4 and some N_2O

energy used in growing and processing the bioenergy feedstock (Spatari et al. 2005).

A significant barrier to production of biofuels from grain is the competitive need of the grain for food and feed. Systems to utilize cellulosic biomass are not yet commercially viable, although much research and subsidies are being implemented to stimulate its use. Even if research at the laboratory scale is promising, challenges exist in scaling up the infrastructure to provide a feasible supply chain for cellulosic bioenergy (Richard 2010).

13.3.2 Advantages

- Some of the biofuel production such as Jatropha and oil palms can be grown in dryland and fallow area, through commercial experiences.
- About 70–88 million biogas plants can be run with fresh/dry biomass residues.
- The substrates such as cattle waste and biomass used for this technology are easily available. Their availability to biogas plants can meet the requirement of 12–30 million families.

13.3.3 Disadvantages

- A larger area of land will be required to satisfy global biofuel demand. Projected growth of biofuel crops until 2030 may require over 30 million hectares of land (IEA 2009). However, Field et al. (2008) suggested a need for 1,500 million hectares of land under cultivation of biofuel crops. Melillo et al. (2009)'s calculations show biofuel crops would require 1,600–2,000 million hectares by the year 2100 assuming most fuel demand would be met by biofuels by this time. It is practically impossible to spare such a large area of cropland to grow biofuel plants.
- The land requirement for biofuel crops would compete with that for food and feed crops, causing food prices to increase.
- In many cases for current ethanol production from grain, the fossil fuel associated with use of chemical fertilizers, tractor power, and so on results in an unacceptably small net reduction in fossil fuel use (Scharlemann and Laurance 2008).
- Production systems with suitable enzymes for utilizing cellulosic feedstocks have not yet become commercially viable.
- The resources for biogas generation are not properly managed to generate its maximum biogas potential.
- The lack of availability and the structural operation of biogas digesters are not able to generate and develop family size biogas plants.

The use of husks as a fuel appears to be a promising mitigation option. Husk could be used for direct burning, in biomass gasifier, as briquettes or as solid char. Its relative cost is around US$4 per t CO_2e saved, and the reduction potential ranges from 0.9 to 1.2 t CO_2e ha^{-1} (depending on the level of biomass production). Rice husk can easily be collected at milling facilities, so that this source of renewable energy seems even more promising than utilization of straw (Wassmann and Pathak 2007).

The potential for mitigation is huge, particularly if cellulosic biomass sources can be commercialized. However, the economics are such that biofuels require help from legislation and subsidies to penetrate the market, at least in parts of the USA where currently a proportion of gasoline must be ethanol at certain times of the year more to mitigate air pollution from ozone than to mitigate GHG emissions (Regalbuto 2009), and there is a legislative mandate for 16 billion gallons of cellulosic ethanol by 2022 (Robertson et al. 2008). Similarly, Europe has a mandate that 10 % of all transport fuels be from renewable sources by 2020 (Robertson et al. 2008).

13.4 Mitigation Potential

13.4.1 Technical Mitigation Potential

Figure 13.16 outlines the technical mitigation potential differentiated between management techniques and all affected GHGs. It can clearly be seen that the more sustainable management of croplands has a substantial potential for mitigation.

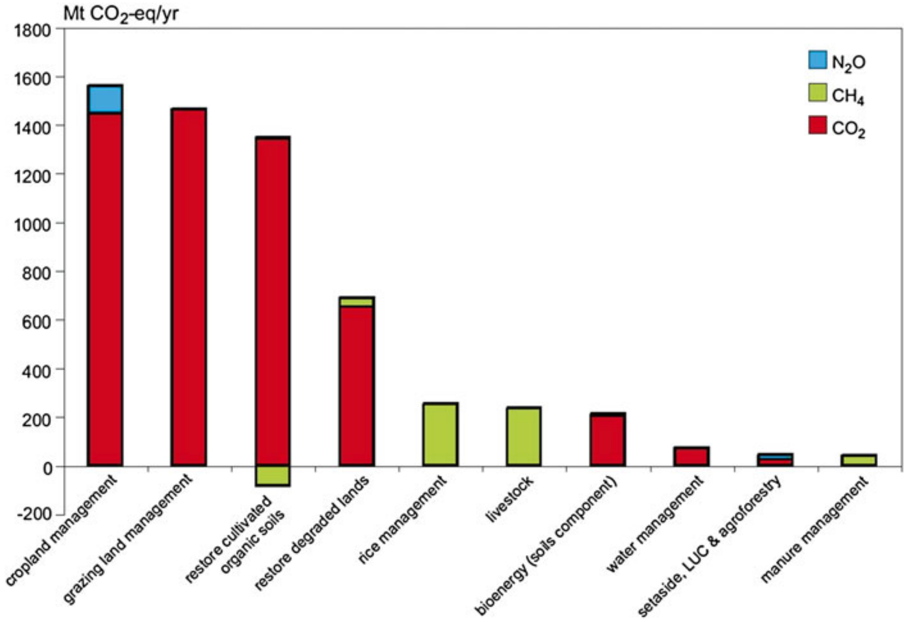

Fig. 13.16 Technical mitigation potential of cropland management options

At low prices of carbon, dominant alternative strategies for land management are those consistent with the existing production such as changes in tillage, fertilizer application, livestock diet formulation, and manure management. Higher prices elicit land-use changes that displace existing production, such as biofuels, and allow for use of costly animal feed-based mitigation options. A practice effective in reducing emissions at one site may be less effective or even counterproductive elsewhere. Consequently, there is no universally applicable list of mitigation practices; practices need to be evaluated for individual agricultural systems based on climate, edaphic, social setting, and historical patterns of land use and management (IPCC 2007a, b, c).

13.4.2 Agricultural Mitigation Potential

The mitigation potential of a suite of agricultural practices that reduce emissions associated with farming and increase carbon storage is estimated to be 1,500–1,600 million tons of carbon dioxide equivalent ($MtCO_2e$) per year at a carbon price of US$ 20 per $MtCO_2e$. The mitigation potential through land-use change is estimated to be a further 1,550 $MtCO_2e$ per year.

Overall potential of agriculture to mitigate carbon (excluding biomass and fossil fuel offsets) is projected to be approximately 5,500–6,000 $MtCO_2e$ per year by 2030 (Smith et al. 2012). The price of carbon determines the global economic potential for agricultural mitigation – the higher the price, the higher the potential.

The global economic potential of mitigation through land-use change (avoided deforestation and degradation, reforestation, and restoration) is estimated to be between 1,270 and 4,230 $MtCO_2e$ per year in 2030 (at carbon prices up to US$ 100 per t CO_2e). About 1,550 $MtCO_2e$ per year can be achieved at a cost under US$ 20 per t CO_2e (Nabuurs et al. 2007).

Sequestering carbon in the soils of croplands, grazing lands, and rangelands offers highest potential source of climate change mitigation from agriculture. These soils can store between 1,500 and 4,500 $MtCO_2e$ per year (Table 13.13) (Smith et al. 2007).

Table 13.13 Effect of proposed measures for mitigating individual greenhouse gas emissions from agricultural systems (Smith et al. 2007)

		Mitigative effects[a]		
Measure	Examples	CO_2	CH_4	N_2O
Cropland management	Agronomy	+		+/–
	Nutrient management	+		+
	Tillage/residue management	+		+/–
	Water management (irrigation, drainage)	+/–		+
	Rice management	+/–	+	+/–
	Agro-forestry	+		+/–
	Set-aside, land-use change	+	+	+
Grazing land management/pasture improvement	Grazing intensity	+/–	+/–	+/–
	Increased productivity (e.g., fertilization)	+		+/–
	Nutrient management	+		+/–
	Fire management	+		+/–
	Species introduction (including legumes)	+	+	+/–
Management of organic soils	Avoid drainage of wetlands	+	–	+/–
Restoration of degraded lands	Erosion control, organic amendments, nutrient amendments	+		+/–
Livestock management	Improved feeding practices		+	+
	Specific agents and dietary additives		+	
	Longer term structural & management changes & animal breeding		+	+
Manure/biosolid management	Improved storage and handling		+	+/–
	Anaerobic digestion		+	+/–
	More efficient use as nutrient source	+		+
Bioenergy	Energy crops, solid, liquid, biogas, residues	+	+/–	+/–

[a] + denotes reduced emissions or enhanced removal (positive mitigation effect)
– denotes increased emissions or suppressed removal (negative mitigation effect)
+/– denotes uncertain or variable response

13.5 Benefits of Mitigation Measures

Since it is difficult to quantify the overall effect of the mitigation measures, it is valuable to look at the effects of implementation of these mitigation measures in specific situations. According to the FAO (2010) implementation of conservation agriculture (which is grouping of several of the methods outlined in cropland management) results in a variety of benefits:

- Higher agricultural productivity, due to improved efficiency in the use of inputs and other resources. The increased agricultural productivity improves food security and reduces vulnerability.
- Greater environmental sustainability, due to improved soil structure and enhanced fertility. This reduces the pressure on the environment and allows for a more beneficial use of the soil.
- Improved livelihoods and social sustainability, due to the accessibility to the technology by all social categories, including the most vulnerable. Sustainable agriculture is not exclusive to certain social groups and as such can benefit all social categories within the country in which it is applied.

According to the FAO (2010) report, long-term yield increases, and output stability can be achieved, while at the same time stopping and reversing land degradation. In addition, the larger outputs are achieved by employing fewer inputs and thus reducing costs. Additionally, the FAO (2010) notes that conservation farming techniques which rationalize the use of labor are particularly helpful in those rural areas where migration and

Table 13.14 Potential agroecological benefits associated with conservation agriculture (FAO 2010)

Agroecological benefits	Resulting from…	Due to…
Progressive suppression of weed growth	Improved soil structure and stability	Reduced tillage
Long-term yield increase	Reduced water and wind erosion	Reduced tillage, soil cover, mulching, intercropping, and crop rotation
	Increased soil fertility, stability and structure.	
	Improved retention of water, nutrients, and soil moisture	
Reduced runoff	Decreased erosion and improved soil structure and water retention capacity	Reduced tillage and soil cover
Improved rooting conditions	Increased soil fertility and stability and improved soil structure	Reduced tillage, soil cover, mulching, intercropping, and crop rotation
Improved agrobiodiversity	Higher biological activity in soil and field	Soil cover and mulching
	Crop diversification	Crop rotation and intercropping
Output stability	Reduced vulnerability to climatic shocks	Improved rooting conditions
	Enhanced biological pest and disease control	Crop rotation
		Higher biological activity in soil and field
Reduced waste of water and inputs	Reduced runoff	Decreased erosion, improved soil structure. and water retention capacity

Table 13.15 Potential environmental benefits associated with conservation agriculture (FAO 2010)

Environmental benefits	Resulting from…	Due to…
Decrease of land degradation	Reduced erosion, higher soil fertility, and improved soil structure	Reduced tillage, soil cover, mulching, intercropping, and crop rotation
	Improved agrobiodiversity	Higher biological activity in soil and field
Reduced downstream sedimentation and siltation	Reduced runoff	Decreased erosion, improved soil structure, and water retention capacity
Reduced contamination of soil and surface and groundwater	Reduced runoff	Decreased erosion, improved soil structure, and water retention capacity
Reduction of CO_2 emissions to the atmosphere	Higher carbon sequestration	Reduced tillage, soil cover, and mulching
Conservation and enhancement of terrestrial- and soil-based biodiversity	Crop diversification	Crop rotation and intercropping
	Higher biological activity	Soil cover and mulching

health emergencies have reduced the labor supply and contributed to the increasing "feminization" of the agricultural sector.

Tables 13.14 and 13.15 summarize the potential agroecological benefits associated with conservation agriculture found in the FAO (2010) report.

The socioeconomic benefits of conservation agriculture implementation are illustrated in Table 13.16.

Table 13.17 outlines the economic benefits of conservation agriculture implementation by the FAO. Net income from the same area is almost double compared to the income from conventional tillage, and the labor hours are also reduced. While reduced labor requirements might be a constraint to the implementation in other situations, the FAO (2010) notes that in Lesotho the rationalization of the use of labor is particularly

Table 13.16 Potential socioeconomic benefits associated with conservation agriculture (FAO 2010)

Socioeconomic benefits	Resulting from…	Due to…
Increased food security	Long-term yield increase and output stability	Reduced erosion, higher soil fertility, improved soil structure, and improved retention of water, nutrients, and soil moisture. Enhanced biological pest and disease control
	Crop diversification	Reduced vulnerability to climatic shocks
		Crop rotation and intercropping
Increased net profitability	Long-term yield increase and output stability	Reduced erosion, higher soil fertility, improved soil structure, and improved retention of water, nutrients, and soil moisture
		Enhanced biological pest and disease control
		Reduced vulnerability to climatic shocks
	Reduction of on-farm costs	Savings in labor, machinery, and (in the medium-term) chemical inputs (herbicides, fertilizer, and pesticides, depending on the technology adopted)
Technology sustainability	Suitability to different farming systems and agroecological environments	Appropriate combination of tillage techniques, equipment, and inputs

Table 13.17 Comparison of conventional and conservation agriculture cropping costs for smallholders at two locations in Paraguay (FAO 2010)

	Edelira[a]			San Pedro[b]		
Crop/cost item (US$ 1998)	Conventional tillage (1)	Conservation tillage (2)	Ratio (1/2)	Conventional tillage (1)	Conservation tillage (2)	Ratio (1/2)
Farm area (ha)	15.6	15.6	–	6.8	6.8	–
Labor (person-days)	287	240	1.20	164	163	1.01
Net farm income (US$/year)	2,570	4,272	0.60	1,010	2,229	0.45
Return to labor (US$/day)	8.95	17.80	0.50	6.16	13.67	0.45

[a] Average of 3 farms that switched from conventional to no-till with green manure crop system
[b] Average of 2 farms that switched from conventional to no-till with green manure crop system

helpful in the rural areas in Lesotho where migration and health emergencies have reduced the labor supply and contributed to the increasing feminization of the agricultural sector.

13.6 Future Prospects and Conclusions

13.6.1 Future Prospects

Trends in GHG emissions in the agricultural sector depend mainly on the level and rate of socioeconomic development, human population growth and diet, application of adequate technologies, climate and non-climate policies, and future climate change. Consequently, mitigation potentials in the agricultural sector are uncertain, making a consensus difficult to achieve and hindering policy making. However, agriculture is a significant contributor to GHG emissions. Mitigation is unlikely to occur without action, and higher emissions are projected in the future if current trends are left unconstrained. According to current projections, the global population will reach 9 billion by 2050, an increase of about 50 % over current levels (Cohen 2003). Because of these increases and changing consumption patterns, some analysts estimate that the production of cereals will need to roughly double in the coming decades

(Green et al. 2005). Achieving these increases in food production may require more use of N fertilizer, leading to possible increases in N_2O emissions, unless more efficient fertilization techniques and products can be found (Galloway 2003). Greater demands for food could also increase CH_4 emissions from enteric fermentation if livestock numbers increase in response to demands for meat and other livestock products. As projected by the IMAGE 2.2 model, CO_2, CH_4, and N_2O emissions associated with land use vary greatly between scenarios (Strengers et al. 2004), depending on trends towards globalization or regionalization, and on the emphasis placed on material wealth relative to sustainability and equity.

Some countries are moving forward with climate and non-climate policies, particularly those linked with sustainable development and improving environmental quality. These policies will likely have direct or synergistic effects on GHG emissions and provide a way forward for mitigation in the agricultural sector. Moreover, global sharing of innovative technologies for efficient use of land resources and agricultural inputs, in an effort to eliminate poverty and malnutrition, will also enhance the likelihood of significant mitigation from the agricultural sector.

Mitigation of GHG emissions associated with various agricultural activities and soil carbon sequestration could be achieved through best management practices, many of which are currently available for implementation. Best management practices are not only essential for mitigating GHG emissions but also for other facets of environmental protection such as air and water quality management. Uncertainties do exist, but they can be reduced through finer scale assessments of best management practices within countries, evaluating not only the GHG mitigation potential but also the influences of mitigation options on socioeconomic conditions and other environmental impacts.

The long-term outlook for development of mitigation practices for livestock systems is encouraging. Continuous improvements in animal breeds are likely, and these will reduce the GHG emissions per kg of animal product. Enhanced production efficiency due to structural change or better application of existing technologies is also generally associated with reduced emissions, and there is a trend towards increased efficiency in both developed and developing countries. New technologies may emerge to reduce emissions from livestock such as probiotics, a methane vaccine, or methane inhibitors. However, increased world demand for animal products may mean that while emissions per kg of product decline, total emissions may increase.

Recycling of agricultural by-products, such as crop residues and animal manures, and production of energy crops provides opportunities for direct mitigation of GHG emissions from fossil fuel offsets. However, there are barriers in technologies and economics to using agricultural wastes and in converting energy crops into commercial fuels. The development of innovative technologies is a critical factor in realizing the potential for biofuel production from agricultural wastes and energy crops. This mitigation option could be moved forward with government investment for the development of these technologies and subsidies for using these forms of energy.

A number of agricultural mitigation options which have limited potential now will likely have increased potential in the long term. Examples include better use of fertilizer through precision farming, wider use of slow and controlled release fertilizers and of nitrification inhibitors, and other practices that reduce N application (and thus N_2O emissions). Similarly, enhanced N use efficiency is achievable as technologies such as field diagnostics, fertilizer recommendations from expert/decision support systems, and fertilizer placement technologies are developed and more widely used. New fertilizers and water management systems in paddy rice are also likely in the longer term.

Possible changes to climate and atmosphere in the coming decades may influence GHG emissions from agriculture and the effectiveness of practices adopted to minimize them. For example, atmospheric CO_2 concentrations, likely to double within the next century, may affect agroecosystems through changes in plant growth rates, plant litter composition, drought tolerance, and nitrogen demands (Long et al. 2006).

Similarly, atmospheric nitrogen deposition also affects crop production systems as well as changing temperature regimes, although the effect will depend on the magnitude of change and response of the crop, forage, or livestock species. For example, increasing temperatures are likely to have a positive effect on crop production in colder regions due to a longer growing season (Smith et al. 2005). In contrast, increasing temperatures could accelerate decomposition of soil organic matter, releasing stored soil carbon into the atmosphere (Smith et al. 2005). Furthermore, changes in precipitation patterns could change the adaptability of crops or cropping systems selected to reduce GHG emissions. Many of these effects have high levels of uncertainty; but demonstrate that practices chosen to reduce GHG emissions may not have the same effectiveness in the coming decades. Consequently, programs to reduce emissions in the agricultural sector will need to be designed with flexibility for adaptation in response to climate change.

Overall, the outlook for GHG mitigation in agriculture suggests significant potential. Current initiatives suggest that identifying synergies between climate change policies, sustainable development, and improvement of environmental quality will likely lead the way forward to realization of mitigation potential in this sector.

The organic and sustainable farming systems can and must play an important role in addressing climate change. These systems have been proven to help farmers and ranchers reduce GHG emissions and increase storage of carbon in agricultural soils. These systems can also increase the resilience of their farming and ranching operations to deal with the climatic changes that appear likely under global warming scenarios. They are also the best systems for minimizing other conservation and environmental impacts from agricultural production.

Major points from the research considered in this chapter are the following:

- Protecting grassland and pasture-based agricultural systems and converting row crop systems to grass-based systems can provide for significant levels of retained and newly sequestered soil carbon.
- No-till likely does not sequester new carbon in the soil. The establishment of sustainable and organic systems that include use of cover crops and green manures and conversion from annuals to perennials for pastures and grassland systems will increase carbon sequestration.
- High levels of synthetic fertilizer can reduce soil carbon as well as increase NO_2 emissions. Sustainable and organic systems reduce or eliminate synthetic fertilizer use through the use of nitrogen-fixing plants in rotations, use of green manures and biofertilizers, and use of animal manures integrated into cropping systems or as part of intensively managed rotational grazing systems. These systems can also retain more nitrogen in soils, reducing nitrogen runoff and leaching which also contribute to NO_2 emissions.
- Sustainable and organic livestock production systems that include pastures, perennial forages, and the effective management, composting, and incorporation of manure can significantly lower methane emissions from livestock production.
- Sustainable and organic agricultural systems provide for better management of water, control soil erosion, and provide conservation benefits in addition to the reduction of GHG emissions that can increase the environmental and economic resilience of farming systems and better enable farmers to cope with rapid climate change.
- Farmers and ranchers have significant opportunities to lower energy use on-farm and to generated on-farm energy, especially solar and wind power. On-farm biofuel production can be based on incorporation of perennial feedstocks or new crops in resource-conserving crop rotations that can result in overall reduction of net GHG emissions from the farm or ranch.
- The sustainable and organic systems that result in lowered GHG emissions and increased carbon sequestration also provide significant conservation and environmental benefits and increase the overall health of soils which can increase agricultural production as well.

These sustainable and organic farming systems provide the best long-term approach to dealing with climate change; the best future for our farmers, ranchers, and rural communities; and the best overall food and farming system for our people.

13.7 Conclusions

The IPCC has reported that agriculture is responsible for over a quarter of total global greenhouse gas emissions (Brown 2005). Given that agriculture's share in global gross domestic product (GDP) is about 4 %, these figures suggest that agriculture is highly greenhouse gas intensive. Innovative agricultural practices and technologies can play a role in climate mitigation and adaptation. This adaptation and mitigation potential is nowhere more pronounced than in developing countries where agricultural productivity remains low; poverty, vulnerability, and food insecurity remain high; and the direct effects of climate change are expected to be especially harsh. Creating the necessary agricultural technologies and harnessing them to enable developing countries to adapt their agricultural systems to changing climate will require innovations in policy and institutions as well. In this context, institutions and policies are important at multiple scales.

Travis Lybbert and Daniel Sumner (Mimura et al. 2007) suggest six policy principles:

- The best policy and institutional responses will enhance information flows, incentives, and flexibility.
- Policies and institutions that promote economic development and reduce poverty will often improve agricultural adaptation and may also pave the way for more effective climate change mitigation through agriculture.
- Business as usual among the world's poor is not adequate.
- Existing technology options must be made more available and accessible without overlooking complementary capacity and investments.
- Adaptation and mitigation in agriculture will require local responses, but effective policy responses must also reflect global impacts and interlinkages.
- Trade will play a critical role in both mitigation and adaptation, but will itself be shaped importantly by climate change.

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A Road Map Ahead

14

Abstract

Climate change will make the task of feeding a growing global population and providing the basis for economic growth and poverty reduction more difficult under a business-as-usual scenario, due to adverse impacts on agriculture, requiring spiraling adaptation and related costs. No single approach can meet all of the complex challenges, and decisive action is needed across a wide front. This is perhaps unsurprising, given the diversity and scale of the challenges, and the need for the global food system to deliver much more than just food, and food security in the future. The suggested priorities for policy makers include spreading best practices; investing in new knowledge; making sustainable food production central in development; working on the assumption that there is little new land for agriculture; promoting sustainable intensification, including the environment in food system economics; reducing waste both in high- and low-income countries; improving the evidence based upon which decisions are made and developing metrics to assess progress; anticipating major issues with water availability for food production; working to change consumption patterns; and empowering citizens. Ten key dimensions need to be followed for promoting the sustainable agricultural practices by implementing a program of action covering both adaptation and mitigation measures through four functional areas, namely, research and development; technologies, products, and practices; infrastructure; and capacity building.

Keywords

Future prospects • Priorities for action • Program of action • Key dimensions • Adaptation • Mitigation

14.1 Future Prospects

Early action on climate change in the agricultural sector allows countries to prepare for near- and long-term agricultural adaptation and mitigation action, closely linked with national food security and developmental efforts. The concept of climate-resilient agriculture focuses on maximizing

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benefits and minimizing negative trade-offs across the multiple objectives that agriculture is being called upon to address: food security, development, and climate change adaptation and mitigation.

There is as yet no blueprint for climate-resilient agriculture. However, there are a number of "early action" measures countries and communities could take to facilitate confidence, capacity, knowledge, and experience to transition to sustainable, climate-resilient agricultural production systems. Such measures include data collection, policy development, and the support of demonstration activities. Pursuing early action activities will result in country-specific data and knowledge as well as experience with agricultural practices and policies that could inform long-term national strategies. A strategy that brings together prioritized action, financial incentives, investment policies, institutional arrangements, tenure security, and aggregating mechanisms constitutes an important step in the transition to climate-resilient agriculture. Specific recommendations for further research include the following.

14.1.1 Trade Dimensions

Feeding the world's population in a context of climate change will require a gradual and significant expansion of transborder exchanges of agricultural products. It will be imperative to ensure a mutually supportive approach between climate change and trade policies as they relate to agriculture. The biophysical impacts of climate change will alter crop and animal productivity and will further accentuate current trends towards higher food prices. As a result, developing countries' agricultural imports are expected to double by 2050 due to climate change. This evolution is mirrored by a similar increase in developed-country exports. These changes will affect individual countries differently depending on the extent to which they rely on agricultural trade as part of their food security and development strategy. International trade, combined with increased investment in agriculture, can provide an important mechanism to offset climate-induced production decreases in certain regions and secure access to and availability of food that otherwise may be scantly accessible through domestic production.

Some of the climate change mitigation (response) measures that have emerged in recent years – such as carbon standards and labeling, subsidies for reducing greenhouse gas emissions or promoting alternative energy sources (e.g., biofuels), discussions on border tax adjustments, and free emission allowances under cap-and-trade schemes – may pose challenges to existing trade agreements, depending on how they are designed. Overall, however, good-faith climate change policies are unlikely to breach existing multilateral trade rules, either because they would not be discriminatory or because, if they are, they may be covered by the general exception under the World Trade Organization's (WTO) General Agreement on Tariffs and Trade (GATT) Article XX. Many potential conflicts can be avoided if international consensus on a climate change framework is reached. Possible avenues to advance discussions on trade and climate change can be explored under the Convention and/or in the multilateral trading system.

14.1.2 Enabling Conditions

Adopting agricultural practices that are able to withstand changes in climate and contribute to the reduction of greenhouse gas emissions requires the application of new technologies, the modification of existing ones, and changes to relevant laws and policies. Technology deployment and related capacity building in agriculture come with significant costs for which developing countries, in particular, need financial support.

Under the Cancun Agreements, developed countries confirmed their commitment to provide new and additional resources, including forestry and investments through international institutions, approaching US$30 billion for the period 2010–2012 and to mobilize US$100 billion annually by 2020. In the context of agricultural mitigation and adaptation, the following international financing channels may be considered: the Global Environment Facility Trust Fund, UNFCCC and Kyoto Protocol-mandated financing, and, in the future, the Green Climate Fund. Relevant mechanisms to channel mitigation finance for agriculture into developing countries include a reformed clean development mechanism and finance for nationally appropriate mitigation actions or for reducing emissions from deforestation and forest degradation.

Although international climate finance is likely to be scaled up in the future, it is unlikely to address the investment needs for adaptation and mitigation in developing countries. It is, therefore, necessary to use public funds strategically to remove investment barriers and facilitate private investment and to effectively blend traditional agricultural finance with climate finance. Capacity building and institutional strengthening have to complement these efforts to enable individuals, communities, institutions, and other entities to make effective use of available knowledge, resources, and technologies.

The Cancun Agreements defined the broad architecture and functions of a technology mechanism, although without providing the specifics on how the bodies under the mechanism should operate, what their precise priorities should be, or how their activities would be funded. Existing national technology needs assessments to identify agriculture and forestry as a priority sector. Harnessing the potential of the technology mechanism to promote the research and development, demonstration, deployment, diffusion, and transfer of agricultural mitigation and adaptation technologies requires the mapping of possible options, proposals, and points of intervention in current discussions about the operationalization of the mechanism.

14.1.3 Measurement and Performance

The Convention formulates requirements for performance and benefits measurement for both mitigation and adaptation. Reporting on vulnerability and adaptation occurs through national communications, in relation to national adaptation programs of action in least-developed countries, and in the context of the operations of the Adaptation Fund for measurement of adaptation performance, there is no consensus on indicators, frameworks, or methods to use, but emerging practice indicates that results-based frameworks are a suitable approach to track progress in implementing specific adaptation actions and to ensure accountability for the use of adaptation funds.

Approaches to measure mitigation impacts in agriculture already exist at international, national, sectoral, and project levels. Although there is relatively strong consensus on agricultural greenhouse gas reporting frameworks, measurement of agricultural mitigation actions is hampered by inherent variability in agricultural emissions and removals and by a lack of available data and limited capacities for measurement in many countries. The former can be provided by strengthening existing agricultural monitoring and evaluation systems. Even within developed countries that have elected to account for cropland and grazingland emissions in the Kyoto Protocol's first commitment period, uncertainties associated with agricultural emissions range between 13 and 100 %. Therefore, there is a strong global interest in improving the emission factors of the IPCC and for individual countries to move towards more accurate and precise measurement frameworks.

Given the need for increased food production in the future, efficiency-accounting approaches that incentivize increased food output while reducing the intensity of greenhouse gas emissions per unit of output are relevant. Efficiency-accounting (life cycle) approaches measure the emissions intensity per unit of output. Methods are still under development for many products are data demanding. Given the diversity of agricultural production systems, standardized approaches may not suite all contexts, presenting an obstacle to comparability within and among countries.

14.1.4 Sensitization of Stakeholders About Climate Change and Its Impacts

Considering the impacts of future climate change on sustainability and productivity of agriculture, especially in the developing countries like India, there is an urgent need to sensitize the farmers, extension workers, and other stakeholders involved in supply chain management about the climate change-associated changes in incidence of pests and diseases of major crops in their regions and the different adaptation strategies to cope with the situation. This can be achieved through organization of awareness campaigns, training, and capacity-building programs, development of learning material and support guides for different risk scenarios of pest, etc.

14.1.5 Farmers' Participatory Research for Enhancing Adaptive Capacity

The decision-making ability and adaptive capacity of farmers can be enhanced through the integration of a farmers' participatory and multidisciplinary research approach involving research and developmental organizations and farmers as equal partners. This will help to improve the channels of communication between researchers and farmers for dissemination of knowledge and information regarding the current advances in the provision of weather and climate information and weather-based agro-advisory services for facilitating operational decisions at farm level. A decision support system (DSS) involving mechanisms for collection and dissemination of information on insect–pest data under diverse environmental conditions for improved assessments well in advance needs to be developed. In view of changing pest scenario due to climate, our future research programs should focus on the search for more general forms of resistance against various classes of insects or diseases under abiotically stressful environments.

14.1.6 Promotion of Resource Conservation Technologies

Shrinking resource base due to anthropogenic developmental activities is a major challenge ahead for humanity. Conservation of natural resources can be promoted by giving incentives to the farmers those who are adopting environmental conserving, pest controlling activities such as organic farming, biocontrol, integrated pest management, habitat conservation for important insect pollinators, etc. Strategies for adaptation and coping could benefit from combining scientific and indigenous technical knowledge (ITK), especially in developing countries where technology is least developed. ITK is helpful in adapting the adverse effects of changing climate, e.g., application of natural mulches helps in suppression of harmful pests and diseases besides moderating soil temperatures and conservation of soil moisture. Further more study towards integrating indigenous adaptation measures in global adaptation strategies and scientific research is required.

14.2 Priorities for Action

Addressing food security and climate change challenges has to be done in an integrated manner. To increase food production and to reduce emissions intensity, thus contributing to mitigate climate change, food systems have to be more efficient in the use of resources. To ensure food security and adapt to climate change, they have to become more resilient.

This has to happen globally, worldwide, and everywhere. Increased efficiency in one part of the world provides food and income where it takes place, but it also provides more food, globally, and thus can provide food elsewhere and reduce its cost, globally. With increased risks, increasing resilience of the worldwide food system also means that efficiency and resilience have to be improved everywhere, so as to spread risk. Therefore, climate resilient agriculture is a dynamic approach that concerns all farmers, all over the world. But developing countries are more at risk of climate change and food insecurity. They also have more potential for mitigation (and adaptation?), because they have to increase their production more and because there is an important efficiency gap. On the other hand developing countries have less means, policies, and institutions to address these challenges.

The changes outlined have to be supported by efforts to harness consumption. Consumption patterns play an important role in the increased demand on agriculture, on the impact of food systems on environment, and also on food security. More sustainable patterns of consumption would, in particular, play an essential role to mitigate climate change (HLPE 2012). Sustainable diets are defined by FAO as "those diets with low environmental impacts that contribute to food and nutrition security and to healthy lives for present and future generations. Sustainable diets should be protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable, nutritionally adequate, safe and healthy, while optimizing natural and human resources" (FAO 2010). But, to a great extent, the tools, policies, and institutions that could influence consumption and diets, especially in developed countries, are very different from those that would be used to transform agricultural systems.

No single approach can meet all of the complex challenges, and decisive action is needed across a wide front. This is perhaps unsurprising, given the diversity and scale of the challenges, and the need for the global food system to deliver much more than just food, and food security in the future. The attention of policy makers will therefore shift to the question of prioritization – where to focus efforts and how best to deploy scarce resources. The following 12 cross-cutting actions (these are not in any order of importance) are priorities for policy makers as suggested.

14.2.1 Key Priorities for Action for Policy Makers

- Spread best practice.
- Invest in new knowledge.
- Make sustainable food production central in development.
- Work on the assumption that there is little new land for agriculture.
- Promote sustainable intensification.
- Include the environment in food system economics.
- Reduce waste – both in high- and low-income countries.
- Improve the evidence base upon which decisions are made and develop metrics to assess progress.
- Anticipate major issues with water availability for food production.
- Work to change consumption patterns.
- Empower citizens.

14.2.1.1 Spread Best Practice

There are major advances to be made using existing knowledge and technologies to raise yields, increase input use efficiency, and improve sustainability. But this will require significant investment of both financial and political capitals to ensure that food producers have the right incentives and are equipped with the necessary skills to meet current and future challenges. The following priorities to achieve these ends have been highlighted: improvements in extension and advisory services in high-, middle-, and low-income countries and strengthening of rights to land and natural resources in low-income countries. Adopting proven models of extension and knowledge exchange to build human and social capital is critical for addressing all aspects of food production from sustainable agronomy to business skills.

14.2.1.2 Invest in New Knowledge

There is a consensus among the results of food system models that one of the most critical drivers of future food supply is the rate of growth of yields due to new science and technology. New knowledge is also required for the food system to become more sustainable, to mitigate and adapt to climate change, and to address the needs of the world's poorest. These challenges will require solutions at the limits of human ingenuity and at the forefront of scientific understanding. No one technology or intervention is a panacea, but there are real sustainable gains to be made by combining biotechnological, agronomic, and agroecological approaches. Because of the significant time lags in reaping the benefits of research, investment in new knowledge needs to be made now to solve problems in the coming decades. Investment needs to occur not only in the important field of biotechnological research but across all the areas of the natural and social sciences involved in the food system.

- Precision in climate change prediction with higher resolution on spatial and temporal scales.
- Linking of predictions with agricultural production systems to suggest suitable options for sustaining agricultural production.
- Preparation of a database on climate change impacts on agriculture.
- Evaluation of the impacts of climate change in selected locations.
- Development of models for pest population dynamics.

14.2.1.3 Make Sustainable Food Production Central in Development

The "Cinderella status" of primary food production in international development financing has for too long ignored the crucial role that it plays in rural and urban livelihoods. There is evidence from a series of recent initiatives that this neglect is now changing. Such investment is not only about food production but also the web of people, communities, and physical infrastructure that surrounds it. Investment in the sector offers a pro-poor model of economic growth with much wider positive impacts on low- and middle-income economies and a means of producing a broader range of public goods. Development trajectories should be chosen to help food producers in low-income countries adapt to the effects of climate change to which they are likely to be disproportionately exposed. Development of sustainable production systems that avoid the mistakes made by countries which moved out of the low-income class in earlier times is required. Investment in infrastructure and capacity building is needed at a scale which will be realized only by innovative new partnerships between governments, multilateral bodies, and the private sector.

14.2.1.4 Work on the Assumption that There Is Little New Land for Agriculture

Relatively little new land on a global scale has been brought into food production in the last 40 years. Although modest amounts may in future be converted to agriculture, it is concluded that major expansion is unwise. In particular, it is now understood that one of the major ways that food production contributes to greenhouse gas emissions is through land conversion, particularly of forests. Only in exceptional circumstances can conversion of forests (especially tropical rainforests), natural grasslands, and wetlands to agricultural land be justified. It is also recognized that while some biodiversity can be maintained on land used for food production, a very significant fraction, especially in the tropics, requires relatively undisturbed non-agricultural habitats. In contrast to land conversion, the restoration of degraded agricultural land can be an important means of increasing the food supply and a good use of international development monies.

14.2.1.5 Promote Sustainable Intensification

It follows that if there is relatively little new land for agriculture, more food needs to be produced and achieving sustainability is critical; then sustainable intensification is a priority. Sustainable intensification means simultaneously raising yields, increasing the efficiency with which inputs are used, and reducing the negative environmental effects on food production. It requires economic and social changes to recognize the multiple outputs required of land managers, farmers, and other food producers and a redirection of research to address a more complex set of goals than just increasing yield.

14.2.1.6 Include the Environment in Food System Economics

The food system relies on a variety of services that are provided without cost by the environment – what are now called ecosystem services. The food system may negatively affect the environment and hence harm the same ecosystem services it relies upon or affect those that benefit other sectors. Understanding the economics of ecosystem services is a very active area of current research, and incorporating the true costs (or benefits) of different productions systems on ecosystem services is a powerful way to incentivize sustainability. It also helps identify situations where moves to increased sustainability impact upon the poorest people who will require help and support.

14.2.1.7 Reduce Waste – Particularly in High- and Low-Income Countries

Food is wasted at all stages of the food chain: in high-income countries, waste tends to be concentrated at the consumer end and in low-income countries more towards the producer's. Reducing food waste is an obvious priority and should be accorded very high priority. It is also an area where individual citizens and businesses, particularly in high-income countries, can make a clear contribution.

14.2.1.8 Improve the Evidence Base upon Which Decisions Are Made and Develop Metrics to Assess Progress

Specific recommendations are needed for the creation of a global, spatially explicit, open-source data base for the analysis of agriculture, the food system, and the environment and the setting up of an International Food System Modeling Forum to enable a more systematic comparison of different models, to share results, and to integrate their work better to meet the needs of policy makers.

14.2.1.9 Anticipate Major Issues with Water Availability for Food Production

While a series of issues concerning competition for the inputs for food production has been highlighted, it is growing pressure on water supplies that is likely to be experienced first. The dangers come from higher demand for water from other sectors, the exhaustion of aquifers, and changes in precipitation patterns, higher sea levels, and altered river flows caused by climate change. Incentives to encourage greater efficiency of water use and the development of integrated water management plans need to be given high priority.

14.2.1.10 Work to Change Consumption Patterns

The informed consumer can effect change in the food system by choosing to purchase items that promote sustainability, equitability, or other desirable goals. Clear labeling and information is essential for this to happen. Governments are likely to need to consider the full range of options to change consumption patterns including raising citizen awareness, approaches based on behavioral psychology, voluntary agreements with the private sector, and regulatory and fiscal measures. Building a societal consensus for action will be a key to modifying demand.

14.2.1.11 Empower Citizens

Investment is needed in the tools to help citizens hold all other actors (and themselves) to account for their efforts to improve the global food system. Examples include the better provision and publication of information on the commitments of different groups, the extent to which they have acted on their commitments, and through information on a food system "dashboard," a measure of their effectiveness. Modern ITC needs to be mobilized to provide, for example, real-time hunger surveillance and to allow farmers and consumers to give feedback on what is working and not working in hunger reduction efforts.

These priorities will need to be pursued by a wide range of actors in the global food system, often acting in concert. These include UN and other international organizations, governments, the private sector, non-governmental organizations, and the research community. Indeed, individual consumers could also play an important role, as outlined above.

14.3 Program of Action (PoA)

The following ten key dimensions (Fig. 14.1) have been identified for promoting the sustainable agricultural practices by implementing a

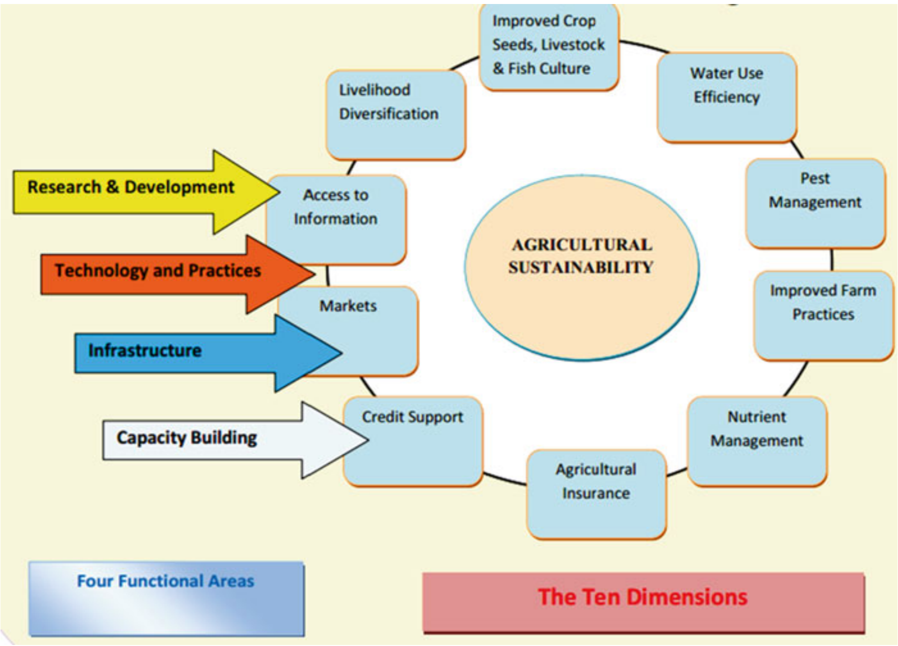

Fig. 14.1 Ten dimensions and four key functional areas for program of action

program of action (POA) covering both adaptation and mitigation measures:

- Improved crop seeds
- Livestock and fish cultures
- Water-use efficiency
- Pest management
- Improved farm practices
- Nutrient management
- Agricultural insurance
- Credit support; markets
- Access to information
- Livelihood diversification

These key areas need to be addressed due to the risks emanating from climate change. Each of these dimensions has then to be analyzed in the context of four functional areas, viz., research and development, technology and practices, and infrastructure and capacity building for identifying adaptation and mitigation needs in a multidimensional and cross-sectoral matrix (Fig. 14.1). New research activities and schematic interventions would also be necessary for meeting the adaptation and mitigation needs in the long term.

14.3.1 Research and Development

Customization of hybrid or high-yielding varieties of seeds to the specific needs of each agroclimatic zone (ACZ) would be the main thrust area under the theme of research and development. An expansion in the scope of livestock research programs to cover other farm animals besides cattle would prove beneficial in the long run. Research on better fodder and adaptive fish varieties needs to be initiated. Use of biotechnology for the development of plant, animal, and fish varieties that are more climate resistant and have higher resistance to biotic and abiotic stresses is an important prerequisite for dealing with climatic variabilities and heat stresses. Development of predictive models for pest and disease surveillance would also be supported and strengthened. At the economic level, research on market requirements and new forms of credit assessment and risk management systems needs to be promoted. The details of opportunities for new interventions in the functional area of research and development are as follows:

- Development of plant genetic resources with greater adaptive capacity to draught, flood, salinity and high temperature through modified physiological processes and assisted marker selection
- Development of crops with enhanced CO_2 fixation potential to increase productivity and with less water consumption
- Gene manipulation for introducing C4 pathway in important C3 crops
- Discovering novel use of RuBisco enzyme that enables conversion of CO_2 more quickly and effectively
- Development of crops with enhanced water and nitrogen use efficiency for reduced emissions of greenhouse gases in the irrigated agricultural system and utilization of phenomics
- Development of crop, livestock, and fish varieties tolerant to various abiotic stresses
- Establishing agricultural intelligence system
- Development of effective surveillance systems for invasive species in imports
- Development of predictive models for agro-advisory services
- Development of decision support systems for scenario-based planning
- Site-specific data inventories for predictive models
- Development of inventory for all available nutrients
- Development of ICT-based systems and methodologies for accelerated agricultural growth
- Strengthening market research in domestic as well as global demand projections for food and food exports and imports based on climate change variables
- Research on new forms of credit assessment and risk management systems
- Development of appropriately designed insurance schemes for specific climate change impacts

14.3.2 Technologies and Practices

The main thrust area under technology, products, and practices would be the conservation of natural resources through promotion of resource-efficient technologies and practices. Deployment of customized technologies and packages of practices that are specific to regional requirements would be accomplished. Wider dissemination of a larger array of resource conserving technologies and proven products is the need of the hour. Technologies and practices that increase the mitigation potential at the farm level would be propagated and plant and livestock management options that allow for maximum returns would be explored. Product monitoring for quality of farm inputs would be strengthened. The details of opportunities for new interventions in the functional area of technology, products, and practices are as follows:

- Customization of resource conservation technologies (RCT) to suit crop varieties in different agroclimatic conditions
- Introduction of improved pest and weed control methods especially to cater vector-borne incidences
- Change in dietary practices of livestock to curb methane emissions from enteric fermentation
- Planning the sequencing of crops based on their nutrient demands and nutrient uptake efficiencies and residues to suit specific soil conditions
- Recycling of wastes and their conversion into easily transportable and usable forms for their effective utilization in plant nutrient supply
- Quality labeling and specifying microorganism application for agriculture, horticulture, greenhouse products, etc.
- Intermittent flooding during rice cultivation or aeration of rice fields
- Management of feeding schedule of livestock
- Development of integrated farming system to suit specific location needs
- Development of farm ponds, bio-gas plant, and a few fertilizer trees as a combination to improve farm productivity in rainfed areas.
- Development of food and fodder security plan for safeguarding dairy-, poultry-, and other animal-based enterprises
- Promoting greenhouse horticulture combined with animal husbandry and agro-forestry for

enhancing both livelihood and nutrition security.
- Launching a dynamic program in the area of sea-water farming involving salt-tolerant varieties, agro-forestry, and marine aqua-culture

14.3.3 Infrastructure

Infrastructure development is a fundamental need for climate resilient sustainable agriculture. Infrastructure needs to be mainly developed in the water and power sector to promote sustainability of farm operations. End of line connectivity for irrigation water has to be improved for its better availability at the farm level. Dedicated power grids for agriculture should be constructed and access to renewable energy sources to be developed for deployment in agriculture sector. Apart from this, infrastructural requirements to improve rural connectivity for better access to markets and improving supply chain efficiency have also to be met. Creation of additional and improved storage facilities for seeds, food grain, alternative markets, and auction houses and establishment of terminal markets has to be ensured. Further, in the domain of financial and institutional infrastructure, this dimension would cater to the enhanced need for establishing a safety net through effective risk management and easy access to credit and reducing information asymmetry. The details of opportunities for new interventions in the functional area of infrastructure are as follows:

- Creation of alternative markets, auction houses, vegetable centers, terminal markets, etc.
- Reuse/recycle of waste water and treatment of poor quality water including saline water for irrigation purposes.
- Web-based digitized climatic information and forecasting system along with advisories to end-users.
- Creating secondary storages in tail end of canal commands to store water at the time of excess availability for future use during critical periods
- Creating minor irrigation sources including groundwater development structures
- Mobile service to farmers for providing weather information, agri-advisories, and supply of critical inputs
- Development of a safety net infrastructure that includes insurance, emergency relief, and debt waiver
- Broad-basing the scope of current credit delivery system and widening its coverage
- Development of seed bank, fodder and feed bank, and grain bank at all agroclimatic zones
- Development of warehousing and storage capacity for food grains of at least one million tons capacity in major agroclimatic zones
- Development of fodder and food banks with the help of self-help groups (SHG)

14.3.4 Capacity Building

Current capacity building initiatives involve training and demonstration activities to farmers and staff/officials. The scope of such initiatives needs to be expanded to cover demonstrations on a larger array of crops specific to regional weather characteristics and market requirements. Demonstrations of innovative crop and region -specific technologies and practices would be carried out at a more disaggregated level. A more uniform and feasible structure for training of farmers as well as staff/officials should be outlined. Extension education format would have to be linked to technological development and industry. Access to information would be augmented by introducing mobile telephony-based delivery modules for greater outreach. Additionally, farmer–market–industry interfaces should also be strengthened. The details of opportunities for new interventions in the functional area of capacity building are as follows:

- Capacity building of stakeholders of agri-supply chain
- Introduction of mobile phone-based information delivery modules for faster dissemination of knowledge
- To achieve synergy between government and non-government initiatives for identification and strengthening collaboration in cross-cutting areas

- Building of strong farmer–institution interface for quick dissemination of knowledge and faster technology absorption
- Promotion of farmers' participation in professional breeding programs
- Establishment of research and training center for climate risk management in all the agroclimatic zones with facilities such as village resource center with satellite connectivity and a fully equipped meteorological station, etc.

14.4 Conclusions

In general, the tropical regions appear to be more vulnerable to climate change than the temperate regions for several reasons (because of economic and social constraints, greater economic and individual dependence on agriculture, widespread poverty, inadequate technologies, and lack of political power). In the light of possible global warming, plant breeders should probably place even more emphasis on development of heat- and drought-resistant crops. Both crop architecture and physiology may be genetically altered to adapt to warmer environmental conditions. At the national and international levels, the needs of regions and people vulnerable to the effects of climate change on their food supply should be addressed.

It is important to make experimental models for each of the climate change components. Information obtained from climate change studies can help us to predict which components are most likely to become more problematic in the future. Modeling can never be a perfect science, but unless we figure out a way to build planets identical to Earth on which to perform experiments, the virtual planets they describe will remain the best available laboratories for studying future climate change.

Climate change adaptation and mitigation in the agriculture sector will have to be pursued in the context of meeting projected global food production demands. Although there are practices that hold great potential for meeting both needs, there is as yet no international agreement, nor national or global policy framework within which to operate. Given this situation, early action holds great potential for countries to take positive action in the short run that can inform national and international policy, finance, and science. Potential conflicts with the international trading system can be addressed with the continued maturation of global climate policy. The ability to act depends on improved measurement systems, tools, and techniques for adaptation and mitigation. There is some cause for optimism, however, based on the trajectory of work to develop the approaches explained above (priorities for action).

It is important to ask, "What will or should agriculture be like in the next century?" Even if the answer is unknown, the flexibility gained in attempting to imagine the agricultural future should be a useful tool for adaptation to climate change.

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Annexures

Annexure I

Glossary

Abatement Refers to reducing the degree or intensity of greenhouse gas emissions.

Abiotic stress Abiotic stress is defined as the negative impact of nonliving factors on the living organisms in a specific environment. Abiotic stress is essentially unavoidable.

Adaptation (to climate change) Adjustments to current or expected climate variability and changing average climate conditions. This can serve to moderate harm and exploit beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation.

Adaptation benefits Avoided damage costs or accrued benefits following the adoption and implementation of adaptation measures.

Adaptation Fund The Adaptation Fund was established to finance concrete adaptation projects and programs in developing countries that are particularly vulnerable and are Parties to the Kyoto Protocol. The Fund is to be financed with a share of proceeds from clean development mechanism (CDM) project activities and receives funds from other sources. It is operated by the Adaptation Fund Board.

Adaptation strategies A type of adjustment or response to climate change that is based on adapting to changing conditions in the environment usually through some type of technological or institutional innovation. An example of a technological innovation would be the development of new crop varieties or farming techniques. Institutional innovations involve changes in underlying economic, political, and social structures.

Adaptive assessment The practice of identifying options to adapt to climate change and evaluating them in terms of criteria such as availability, benefits, costs, effectiveness, efficiency and feasibility.

Adaptive capacity The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

Aerosol Solid or liquid particles in the earth's atmosphere having sizes on the order of 0.01–10 microns (1 micron = 0.0001 cm). Aerosol has a variety of sources: natural sources include salt particles ejected from the ocean, organic molecules, windblown dust, pollen, and desert sand particles; anthropogenic sources include carbon-based soot particulates from fossil fuel burning and SO_2 emissions from industry that undergo a gas-to-particle conversion. Aerosols are important in the radiative balance of the atmosphere, as they tend to cool the earth's surface by scattering incoming solar radiation back to space.

Afforestation The conversion from other land uses into forest, or the increase of the canopy cover to above the 10 % threshold.

Aging of soils Deposition of polysaccharides and other organic cementing agents by microbial activity in soil.

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Agricultural biodiversity (agrobiodiversity) It is the result of natural selection processes and the careful selection and inventive developments of farmers, herders, and fishers over millennia. Agrobiodiversity is a vital subset of biodiversity.

Agricultural innovation system A system of individuals, organizations, and enterprises focused on bringing new products, processes, and forms of organization into social and economic use to achieve food and nutrition security, economic development, and sustainable natural resource management.

Agroecology An ecological approach to agriculture that views agricultural areas as ecosystems and is concerned with the ecological impact of agricultural practices.

Agroecosystem The organisms and environment of an agricultural area considered as an ecosystem.

Alliance of Small Island States (AOSIS) An ad hoc coalition of low-lying and island countries. These 43 nations are particularly vulnerable to rising sea levels and share common positions on climate change.

Anaerobic digestion Anaerobic digestion is a natural process in which microorganisms break down organic matter, in the absence of oxygen, into biogas (a mixture of carbon dioxide and methane) and digestate (a nitrogen-rich fertilizer).

Analogue climate Climate modeling technique that uses known climate conditions of the past to forecast future conditions that are expected to have similar characteristics. It is assumed that if certain essential conditions in the forecast scenario are similar to the past conditions, then the resulting climate will compare favorably. See the control climate entry in this glossary.

Annex I countries The industrialized countries listed in Annex I to the Convention, which committed to returning their greenhouse gas emissions to 1990 levels by the year 2000 as per Article 4.2 (a) and (b). They have also accepted emission targets for the period 2008–2012 as per Article 3 and Annex B of the Kyoto Protocol. They include the 24 original OECD members, the European Union, and 14 countries with economies in transition. (Croatia, Liechtenstein, Monaco, and Slovenia joined Annex 1 at COP 3, and the Czech Republic and Slovakia replaced Czechoslovakia.)

Annex II countries The countries listed in Annex II to the Convention which have a special obligation to provide financial resources and facilitate technology transfer to developing countries. Annex II Parties include the 24 original OECD members plus the European Union.

Anthropogenic climate change Climate change with the presumption of human influence, usually warming.

Anthropogenic global warming (AGW) Global warming with the presumption of human influence.

Anthropogenic greenhouse emissions Greenhouse gas emissions resulting from human activities.

Aquifers An aquifer is an underground layer of water-bearing permeable rock or unconsolidated materials (gravel, sand, silt, or clay) from which groundwater can be usefully extracted using a well.

Bio drainage Bio drainage is defined as “pumping of excess soil water by deep-rooted plants using their bio-energy.” The bio drainage system consists of fast-growing tree species, which absorb water from the capillary fringe located above the groundwater table. The absorbed water is translocated to different parts of plants, and finally more than 98 % of the absorbed water is transpired into the atmosphere mainly through the stomata.

Biodiversity The total diversity of all organisms and ecosystems at various spatial scales (from genes to entire biomass).

Biofuels A fuel produced from dry organic matter or combustible oils produced by plants. These fuels are considered renewable as long as the vegetation producing them is maintained or replanted, such as firewood, alcohol fermented from sugar, and combustible oils extracted from soybeans. Their use in place of fossil fuels cuts greenhouse gas emissions because the plants that are the fuel sources capture carbon dioxide from the atmosphere.

Bivoltine Refers to organisms having two generations per year.

***Bt* cotton** A genetically modified cotton, which produced the toxin of *Bacillus thuringiensis* (*Bt*) against Lepidoptera larvae.

C3 plant species Plant species with the C3 photosynthetic pathway (the first product in their biochemical sequence of reactions has three carbon atoms) use up some of the solar energy they absorb in a process known as photorespiration, in which a significant fraction of the CO_2 initially fixed into carbohydrates is reoxidized back to CO_2. C3 species tend to respond positively to increased CO_2 because it tends to suppress rates of photorespiration. Some of the current major food staples, such as wheat, rice, and soybean, are C3 plants. In total, 16 of the world's 20 most important food crops would benefit from increased carbon dioxide levels.

C4 plant species In C4 plants (those in which the first product has four carbon atoms), CO_2 is first trapped inside the leaf and then concentrated in the cells which perform the photosynthesis. Although more efficient photosynthetically under current levels of CO_2, these plants are less responsive to increased CO_2 levels than C3 plants. The major C4 staples are maize, sorghum, sugarcane, and millet.

Capacity building In the context of climate change, it refers to the process of developing the technical skills and institutional capability in developing countries and economies in transition to enable them to address effectively the causes and results of climate change.

Carbon cycle The biogeochemical cycle by which carbon is exchanged between the biosphere, geosphere, hydrosphere, and atmosphere of the earth.

Carbon dioxide (CO_2) A greenhouse gas whose atmospheric concentrations have been continually increasing from its preindustrial (1750–1800) levels of 280 parts per million (ppm). It is currently increasing at a rate of 1.3–1.6 ppm per year, with a concentration (1995) ranging from 356 to 360 ppm, depending on location. There is a natural seasonal cycle in CO_2 levels in the atmosphere; CO_2 decreases in summer time when plant productivity consumes CO_2 and increases in winter when biota are less active and respiration exceeds photosynthesis. The main source of CO_2 increase in the atmosphere has been fossil fuel consumption, with biomass burning becoming more significant over the past few decades, currently contributing approximately 30 % as much as fossil fuel emissions.

Carbon finance (carbon market financing) Resources provided to projects generating (or expected to generate) greenhouse gas (or carbon) emission reductions in the form of the purchase of such emission reductions.

Carbon market A popular (but misleading) term for a trading system through which countries may buy or sell units of greenhouse gas emissions in an effort to meet their national limits on emissions, either under the Kyoto Protocol or under other agreements, such as that among member states of the European Union. The term comes from the fact that carbon dioxide is the predominant greenhouse gas and other gases are measured in units called "carbon dioxide equivalents."

Carbon sequestration The process of increasing the carbon content of a reservoir or pool other than the atmosphere.

Certified emission reduction (CER) A Kyoto Protocol unit equal to 1 metric ton of CO2 equivalent. CERs are issued for emission reductions from CDM project activities. Two special types of CERs called temporary certified emission reductions (tCERs) and long-term certified emission reductions (lCERs) are issued for emission removals from afforestation and reforestation CDM projects.

Clean development mechanism (CDM) A mechanism under the Kyoto Protocol through which developed countries may finance greenhouse gas emission reduction or removal projects in developing countries and receive credits for doing so which they may apply towards meeting mandatory limits on their own emissions.

Climate Climate should more accurately be the term applied to the average weather conditions over longer periods of years to decades.

Climate change Climate change refers to any long-term trends in climate over many years or decades, around which climate variability may be evident year on year. Hence, a single warmer or cooler year on its own is not sufficient evidence to assert that climate is changing, but systematic changes in average conditions over many years do provide evidence of a changing climate.

The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition and climate variability attributable to natural causes.

Climate extreme (extreme weather or climate event) The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. For simplicity, both extreme weather events and extreme climate events are referred to collectively as "climate extremes."

Climate forcing An energy imbalance imposed on the climate system either externally or by human activities.

Climate proofing Ensuring that climate risks are reduced to acceptable levels through long-lasting and environmentally sound, economically viable, and socially acceptable changes implemented at one or more of the stages in the project cycle.

Climate-resilient agriculture (CRA) Agriculture that sustainably increases productivity and resilience (adaptation), reduces/removes greenhouse gases (mitigation), and enhances the achievement of national food security and development goals.

Climate variability Climate variability refers to the year-to-year variations, or noise, in the average conditions – meaning that consecutive summers, for example, will not all be the same, with some cooler and some warmer than the long-term average.

Variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability) or to variations in natural or anthropogenic external forcing (external variability).

CO_2 fertilization effect The theory that forests and vegetation will experience enhanced growth or increased net primary productivity under elevated atmospheric CO_2 levels.

Co-benefits Multiple benefits in different fields resulting from one policy, strategy, or action plan.

Communication for development (ComDev) ComDev is a social process based on dialogue using a broad range of tools and methods. ComDev is about seeking change at different levels including listening, establishing trust, sharing knowledge and skills, building policies, debating, and learning for sustained and meaningful change.

Conservation agriculture (CA) Conservation agriculture is an approach to managing agroecosystems for improved and sustained productivity and increased profits and food security while preserving and enhancing the resource base and the environment. It is characterized by three linked principles, namely, continuous minimum mechanical soil disturbance, permanent organic soil cover, and diversification of crop species grown in sequences and/or associations.

Control climate A control climate is a set of climate conditions drawn from the climate record (generally a three-decade period) that is used as a point of departure for assessing model or analogue climate results. The control climate is generally assumed to represent "normal" or "average" climate. See analogue climate in this glossary.

Coping capacity The ability of people, organizations, and systems, using available skills and resources, to face and manage adverse conditions, emergencies, or disasters.

Crop diversification Species diversification through varied crop associations and/or rotations (involving annual and/or perennial crops including trees). Crop diversification is intended to give a wider choice in the production of a variety of crops in a given area so as to expand production-related activities on various crops and also to lessen risks. Crop diversification is generally viewed as a shift from traditionally grown less remunerative crops to more remunerative crops.

Crossbreeding Crossbreeding refers to the process of breeding an animal or plant with purebred parents of two different breeds, often with the intention to create offspring or seedlings that share the traits of both parent lineages, or producing an animal or plant with hybrid vigor.

Damages Include all monetary losses due to climate change impacts, less the amount that can be averted by adaptive measures, and less the economic gains that may be realized by the adaptive measures. This implies that net damages may, in some cases, take on negative values that reflect monetary gains when all factors are considered.

Deficit irrigation An irrigation practice whereby water supply is reduced below maximum levels and mild stress is allowed with minimal effects on yield.

Deforestation The conversion of forest to another land use or the long-term reduction of tree canopy cover below the 10 % threshold.

Diapause A temporary pause in the growth and development of an organism due to adverse environmental conditions.

Disaster A serious disruption of the functioning of a community or a society involving widespread human, material, economic, or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources.

Disaster risk management (DRM) The systematic process of using administrative directives, organizations, and operational skills and capacities to implement strategies, policies, and improved coping capacities in order to lessen the adverse impacts of hazards and the possibility of disaster.

Disaster risk reduction (DRR) The concept and practice of reducing disaster risks through systematic efforts to analyze and manage the causal factors of disasters, including through reduced exposure to hazards, lessened vulnerability of people and property, wise management of land and the environment, and improved preparedness for adverse events.

Drought The phenomenon that exists when precipitation is significantly below normal recorded levels, causing serious hydrological imbalances that often adversely affect land resources and production systems.

Dry spell Short period of water stress during critical crop growth stages and which can occur with high frequency but with minor impacts compared with droughts.

Dryland farming Dryland farming is practiced in areas which are characterized by low and scanty rainfall with erratic distribution, leading to wide fluctuations in crop production.

Drylands Areas characterized by lack of water, which constrains their two major interlinked services of primary production and nutrient cycling.

Dynamical model A model that calculates climatic variables at discrete time intervals during a simulation by using input values that change with time, as compared to a static model simulation such as a “doubled CO_2” scenario that calculates climatic variables at a final endpoint without considering how CO_2 or temperature changes over time.

Earth’s atmosphere A layer of gases surrounding the planet Earth and retained by the earth’s gravity.

Ecosystem The interactive system formed from all living organisms and their abiotic (physical and chemical) environment within a given area. Ecosystems cover a hierarchy of spatial scales and can comprise the entire globe, biomes at the continental scale or small, well-circumscribed systems such as a small pond.

Ecosystem functioning Builds on the processes shaped by interactions among biological communities of both wild and domesticated species, biophysical processes such as water regulation, and nutrient recycling.

Ecosystem resilience The capacity of an ecosystem to absorb external pressure or perturbations through change and reorganization but still retain the same basic structure and ways of functioning.

Ecosystem services Ecological processes or functions that have monetary or nonmonetary value to individuals or society at large. There are supporting services such as productivity or biodiversity maintenance; provisioning services such as food, fiber, or fish; regulating services such as climate regulation or carbon sequestration; and cultural services such as tourism or spiritual and aesthetic appreciation.

Efficient water management In agriculture, efficient water management means getting the right amount of water to the crops at the right time with minimum labor and expense.

E-learning (electronic learning) A term covering a wide set of applications and processes, such as web-based learning, computer-based learning, virtual class rooms, and digital collaboration. It includes the delivery of content via Internet, intranet/extranet (LAN/WAN), audio- and videotape, satellite broadcast, interactive TV, CD-ROM, and more.

El Niño–Southern Oscillation (ENSO) A set of specific interacting parts of a single global system of coupled ocean-atmosphere climate fluctuations that come about as a consequence of oceanic and atmospheric circulation.

Emission reduction unit (ERU) A Kyoto Protocol unit equal to 1 metric ton of CO_2 equivalent. ERUs are generated for emission reductions or emission removals from joint implementation projects.

Emissions trading One of the three Kyoto mechanisms, by which an Annex I Party may transfer Kyoto Protocol units to, or acquire units from, another Annex I Party. An Annex I Party must meet specific eligibility requirements to participate in emissions trading.

Energy efficiency Ratio of energy output of a conversion process or of a system to its energy input.

Enteric fermentation Enteric fermentation is a natural part of the digestive process for many ruminant animals where anaerobic microbes, called methanogens, decompose and ferment food present in the digestive tract producing compounds that are then absorbed by the host animal. A resulting by-product of this process is methane.

Enteric methane Methane emitted as a natural by-product of microbial fermentation of carbohydrates and, to a lesser extent, amino acids in the rumen and the hindgut of farm animals.

Entomopathogens Diseases which infect insects.

Erosion The process of removal and transport of soil and rock by weathering, mass wasting, and the action of streams, glaciers, waves, winds, and underground water.

Evaporation The amount of water that leaves the basin or country as vapor. Evaporation can be beneficial or non-beneficial. Non-beneficial includes evaporation from open water bodies (reservoirs, canals) and from bare soil.

Evapotranspiration (ET) ET is the measurement of moisture that plants and land lose through evaporation and transpiration processes due to heat, humidity, and wind. This amount is what should be replaced while irrigating.

***Ex situ* conservation** The maintenance of genetic material outside of the "normal" environment where the species has evolved and aims to maintain the genetic integrity of the material at the time of collecting. Gene banks, botanical gardens, and zoos are typical examples of *ex situ* conservation activities.

Exposure The nature and degree to which a system is exposed to significant climatic variations.

Extension Rural or agricultural extension services refer to the transfer of research and new practices through farmer training. Successful extension does not merely facilitate the use of new technology or crop alternatives, but empowers farmers to make farm management decisions based on knowledge of options available to them.

Externalities Situations when the effect of production or consumption of goods and services imposes costs or benefits on others which are not reflected in the prices charged for the goods and services being provided.

Farmer field school (FFS) The FFS approach is an innovative, participatory, and interactive learning approach that emphasizes problem solving and discovery-based learning. FFS aims to build farmers' capacity to analyze their production systems, identify problems, test possible solutions, and eventually encourage the participants to adopt the practices most suitable to their farming systems.

Feedbacks (positive, negative) An effect that tends to amplify (+) or reduce (−) a particular process. Warmer temperatures will cause greater evaporation of water from the oceans, for example, potentially leading to greater low cloud formation. Increased low cloud cover would reflect more solar radiation back to space, thus cooling the surface, implying a negative feedback to increased surface temperatures from global warming.

Fertigation It is the application of fertilizers, soil amendments, or other water-soluble products through an irrigation system.

Flux A generic term having different meanings in different fields of study. In radiation studies, it can refer to the amount of radiant energy passing through a unit area (i.e., watts per square meter); in biogeochemical cycles, it may indicate the time rate of change of a given species such as carbon into or out of a particular reservoir (i.e., teragrams of carbon per year).

Food and nutrition security This exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life.

Food losses Decrease in edible food mass available for human consumption throughout the different segments of the supply chain. In addition to quantitative losses, food products can also face a deterioration of quality, leading to a loss of economic and nutritional value.

Food system Involves all processes and activities related to the production, distribution, and consumption of food that can feed a population and affects human nutrition and health. It operates within an infrastructure (roads, rivers, ports, energy and communication networks, etc.) and is influenced by political, social, economic, and environmental aspects.

Food value chain The full range of farms and firms and their successive coordinated value-adding activities that transform raw agricultural materials into food products that are sold to final consumers and disposed after use.

Food waste Food losses resulting from decisions to discard food that still has value. Food waste is most often associated with the behavior of retailers, the food service sector, and consumers, but food waste and losses take place all along food supply chains.

Forage Food of any kind for animals, especially for horses and cattle, as grass, pasture, hay, corn, and oats.

Fossil fuel Refers to fossil source fuels, that is, hydrocarbons found within the top layer of the earth's crust.

General circulation model (GCM) A general circulation model is a generic term used to describe a computer model that simulates how climatic variables such as temperature and precipitation change over time. These models range in complexity from 0-dimensional models to 3-dimensional models and are typically used to address the issue of global warming potential due to increasing atmospheric concentration of greenhouse gases.

Genetic resources (for food and agriculture) This includes any material of plant, animal, microbial, or other origin containing functional units of heredity that is of actual or potential value for food and agriculture. Genetic resources for food and agriculture include the diversity present in agricultural, pastoral, forest, and aquatic production systems or of importance to them: the variety and variability of animals, plants, and microorganisms at the genetic, species, and ecosystem levels that sustain the structure, functions, and processes of production systems. This diversity is often the result of the work of farmers, pastoralists, forest dwellers, and fisherfolk over many hundreds of generations and reflects the diversity of both human activities and natural processes.

Geographical information system (GIS) A system of computing tools and procedures designed for capturing, managing, analyzing, modeling, and displaying spatially referenced data.

Global circulation model Numerical models that represent physical processes in the atmosphere, ocean, cryosphere, and land surface and are the most advanced tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations.

Global warming potential (GWP) An index representing the combined effect of the differing times greenhouse gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation.

Green economy An economy that results in improved human well-being and social equity while significantly reducing environmental risks and ecological scarcities.

Green growth Economic growth that is environmentally sustainable: green, in that it is efficient in use of natural resources; clean, in that it minimizes pollution and environmental impacts; and resilient in accounting for natural hazards and the role of environmental management and natural capital in preventing physical disasters.

Greenhouse gases Those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the earth's surface, the atmosphere, and clouds. This property causes the greenhouse effect. Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) are the primary greenhouse gases in the earth's atmosphere. Moreover, there are a number of entirely man-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Besides CO_2, N_2O, and CH_4, the Kyoto Protocol deals with the greenhouse gases sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs).

Gross national product (GNP) A measure of the market value of goods and services that were produced during a specific period of time, typically measured in terms of an annual rate.

Hazard A dangerous phenomenon, substance, human activity, or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage.

High-regret options They are options valid for future climate but not necessarily for the current climate situation and would therefore represent costs and have possible negative consequences under current climate and therefore require careful consideration in terms of risk analysis.

Hydrological cycle The process of evaporation, transpiration, vertical and horizontal transport of vapor, condensation, precipitation, interception, runoff, infiltration, percolation, storage, the flow of water from continents to oceans, and return.

Impact assessment (of climate change) The practice of identifying and evaluating, in monetary and/or nonmonetary terms, the effects of climate change on natural and human systems. Potential impacts: all impacts that may occur given a projected change in climate, without considering adaptation. Residual impacts: the impacts of climate change that would occur after adaptation.

In situ conservation Implies the maintenance and recovery of viable populations of species in their natural surroundings and – in the case of domesticated or cultivated species on farm – in the surrounding where they have developed their distinctive properties. This method preserves both the population and the evolutionary processes that enable the population to adapt by managing organisms in their natural state or within their normal range.

In vitro conservation (of animal genetic resources) Conservation by cryopreservation of a breed's genetic material (usually semen, embryos, or somatic cells), so that live animals can, if necessary, be regenerated in the future.

In vivo conservation (of animal genetic resources) Conservation of a breed through maintenance of live animal populations, which encompasses both in situ conservation of animals in their typical production environment and *ex situ* in vivo conservation, in non-typical surroundings, such as a research farm.

Inclusiveness Agri-food systems and related agri-food value chains that enable ample participation by commercial input suppliers, farmers, traders, wholesalers, retailers, and consumers as well as commonly marginalized groups (the poor, disabled, youth, and women) in economic activities. Its focus is on wider social participation in agri-food systems and creating positive benefits to communities. It enables and involves even the smallest of participants in the overall agri-food system and others in a community that may not be involved in commercial activities; fair returns to all participants involved in activities; and fair, equal, and safe employment conditions.

Information and communication technologies (ICTs) Technologies designed to access, process, and transmit information. ICTs encompass a full range of technologies – from traditional, widely used devices such as radios, telephones, or TV to more sophisticated tools like computers, mobile phones, or the Internet.

Institutions Encompass formal organizations and contracts as well as informal social and cultural norms and conventions that operate within and between organizations and individuals.

Integrated landscape management An umbrella term for natural resource management systems that recognize the value of various ecosystem services to multiple stakeholders and how this leads them to pursue different land-use objectives or livelihood strategies.

Integrated pest management An ecosystem approach to crop production and protection that combines different management strategies and practices to grow healthy crops and minimize the use of pesticides.

Intergovernmental Panel on Climate Change (IPCC) Established in 1988 by the World Meteorological Organization and the UN Environment Programme, the IPCC surveys worldwide scientific and technical literature and publishes assessment reports that are widely recognized as the most credible existing sources of information on climate change. The IPCC also works on methodologies and responds to specific requests from the Convention's subsidiary bodies. The IPCC is independent of the Convention.

Joint implementation (JI) A market-based implementation mechanism defined in Article 6 of the Kyoto Protocol, allowing Annex I countries or companies from these countries to implement projects jointly that limit or reduce emissions or enhance sinks and to share the emission reduction units. JI activity is also permitted in Article 4.2 (a) of the Framework Convention on Climate Change.

Kyoto mechanisms The three procedures established under the Kyoto Protocol to increase the flexibility and reduce the costs of making greenhouse gas emission cuts. They are the clean development mechanism, emissions trading, and joint implementation.

Kyoto Protocol The Kyoto Protocol to the Framework Convention on Climate Change was adopted at the Third Session of the Conference of the Parties (COP) in 1997 in Kyoto. It contains legally binding commitments, in addition to those included in the UNFCCC. Annex B countries agreed to reduce their anthropogenic GHG emissions (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride) by at least 5 % below 1990 levels in the commitment period 2008–2012. The Kyoto Protocol came into force on February 16, 2005.

Landscape Agricultural landscapes can be described in terms of the three elements: (1) structure – the interaction between environmental features, land-use patterns, and man-made objects; (2) functions – the provision of landscape functions for farmers and for society (environmental services); and (3) value – concerning the value the society places on agricultural landscape and the costs of maintaining and enhancing landscape provisions by agriculture. Because the underlying human and natural processes are subject to change and evolution, landscapes are dynamic systems.

Landscape approach Landscape approach means the management of production systems and natural resources in an area large enough to produce vital ecosystem services and small enough to be managed by the people using the land and producing those services.

Land-use change A greenhouse gas inventory sector that covers emissions and removals of greenhouse gases resulting from direct human-induced land use and land-use change.

Maladaptation Any changes in natural or human systems that inadvertently increase vulnerability to climatic stimuli; an adaptation that does not succeed in reducing vulnerability but increases it instead.

Microfinance The provision of credit and other financial services to small businesses which typically do not have access to such services, aiming to foster economic development.

Mitigation (in relation to climate change) Technological change and substitution that reduce resource inputs and emissions per unit of output. Although several social, economic, and technological policies would produce an emission reduction, with respect to climate change, mitigation means implementing policies to reduce GHG emissions and enhance sinks.

Mitigation (in relation to hazard) The limiting or lessening of the adverse impacts of hazards and related disasters.

Mitigation strategies A type of adjustment or response to climate change that generally involves limiting the emission of greenhouse gases. A tax on the carbon content of fossil fuels that is designed to reduce the use of high-carbon fuels such as coal would be an example of a mitigation strategy. Mitigation strategies are aimed at slowing the potential rate of climate change or preventing it before it occurs.

Montreal Protocol The Montreal Protocol on Substances that Deplete the Ozone Layer, an international agreement adopted in Montreal in 1987.

Mulch tillage Mulch-till is another reduced tillage system in which residue is partially incorporated using chisels, sweeps, field cultivators, or similar farming implements that leaves at least one third of the soil surface covered with crop residue.

Mulching Application of mulch improves the water-use efficiency and helps in water saving by reducing the ET losses and increased yields of a number of field crops during summer months.

Multitrophic Involving several food chain levels, with plants, herbivores, and carnivores constituting the first three levels.

Multivoltine Refers to organisms having more than two generations per year.

Mycorrhiza This is a class of different types of fungi that symbiotically feed off of plants. This symbiosis provides a jointly beneficial relationship between the fungus colony and its host.

National adaptation programs of action (NAPAs) Documents prepared by least developed countries (LDCs) that identify the activities to address urgent and immediate needs for adapting to climate change.

National platform for disaster risk reduction A generic term for national mechanisms for coordination and policy guidance on disaster risk reduction that are multi-sectoral and interdisciplinary in nature, with public, private, and civil society participation involving all concerned entities within a country.

Nationally appropriate mitigation actions (NAMAs) At COP 16 in Cancun in 2010, governments decided to set up a registry to record nationally appropriate mitigation actions seeking international support; to facilitate the matching of finance, technology, and capacity-building support with these actions; and to recognize other NAMAs.

Natural hazard Natural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage.

Networks Networks can be vast repositories of data and/or affiliations of expert contacts on particular issues. Networks allow for knowledge to be shared and managed within and across institutions, thereby facilitating collaboration and research. Networks can also take up an advocacy role.

No-regret options Options that are valid whether climate change will occur as expected or not. In general, they are aimed at increasing the resilience of rural population and reducing their vulnerability to water-related shocks.

Non-Annex I Parties Refer to countries that have ratified or acceded to the United Nations Framework Convention on Climate Change that are not included in Annex I of the Convention.

North Atlantic Oscillation (NAO) One of the large-scale modes of variability coupling ocean temperatures and sea-level pressures, centered on the North Atlantic Ocean basin. The atmospheric circulation normally displays a strong meridional (north-south) pressure contrast, with low pressure in the northern edge of the basin, centered close to Iceland, and high pressure in the subtropics, centered near the Azores.

Ocean acidification Increased concentrations of CO_2 in seawater causing a measurable increase in acidity (i.e., a reduction in ocean pH). This may lead to reduced calcification rates of calcifying organisms such as corals, mollusks, algae, and crustaceans.

Overwinter Passing through or waiting out the winter.

Paludiculture The process of transforming land into a wetland such as a marsh, a swamp, or a bog.

Parasitoid Organism that is parasitic during part of its life cycle, especially one that eventually kills its host.

Partnership brokers Skilled communicators who support interactive collaboration between different types of stakeholders (e.g., public–private partnerships). Partnership brokering should minimize asymmetries of power between actors, ensuring that all stakeholders are heard and their expertise shared appropriately. Depending on the local context, the capacities, and legitimacy available, a brokering role can be played by local government, extension services, civil society organizations, or national agricultural research systems.

Pathogen A disease-causing organism.

Payment for environmental services (PES) An economic instrument designed to provide positive incentives to users of agricultural land and those involved in coastal or marine management. These incentives are expected to result in continued or improved provision of ecosystem services, which, in turn, will benefit society as a whole.

Peatlands Peatlands or organic soils are soils with a substantial layer of organic matter near or at the surface.

Peri-urban agriculture An agricultural system developed around cities to take advantage of local markets for high-value crops (fruits, vegetables, dairy products, etc.).

Permaculture Permaculture (permanent + agriculture) is the conscious design and maintenance of agriculturally productive ecosystems which have the diversity, stability, and resilience of natural ecosystems. It is a land-use and community-building movement which strives for the harmonious integration of human dwellings, microclimate, annual and perennial plants, animals, soils, and water into stable, productive communities.

Phenology Studies that describe the periods of plant and animal life cycle events related to climate.

Pheromones A chemical secreted by an animal, especially an insect that influences the behavior or development of others of the same species.

Pressurized irrigation Pressurized irrigation systems are designed to deliver water with the flow rate and pressure required by the farm irrigation systems, sprinkling or micro-irrigation, and respecting the time, duration, and frequency decided by the farmers.

Rainfed agriculture Agricultural practice relying exclusively on rainfall as its source of water.

Reduce, reuse, recycle The “3 R’s” of waste management. Reduction refers to minimizing the amount of waste generated from a given operation or process. Reuse refers to using the waste material "as is" – such as using waste oil for fuel. Recycling refers to reclaiming materials from the waste product or transforming the waste product into new products.

Reducing emissions from deforestation and forest degradation (REDD) REDD is a mechanism to create an incentive for developing countries to protect, better manage, and wisely use their forest resources, contributing to the global fight against climate change. REDD strategies aim to make forests more valuable standing than they would be cut down by creating a financial value for the carbon stored in trees. Once this carbon is assessed and quantified, the final phase of REDD involves developed countries paying developing countries carbon offsets for their standing forests. REDD is a cutting-edge forestry initiative that aims at tipping the economic balance in favor of sustainable management of forests so that their formidable economic, environmental, and social goods and services benefit countries, communities, biodiversity, and forest users while also contributing to important reductions in greenhouse gas emissions.

Reducing emissions from deforestation and forest degradation plus (REDD+) REDD+ strategies go beyond deforestation and forest degradation and include the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks in reducing emissions**.**

Reforestation The reestablishment of forest formations after a temporary condition with less than 10 % of canopy cover due to human-induced or natural perturbations (FAO 2000).

Relative humidity The amount of water vapor (vapor pressure) in a given parcel of air divided by the maximum amount of water vapor the parcel of air could contain at a given temperature (saturation vapor pressure) before it would begin to condense into water droplets.

Removal unit (RMU) A Kyoto Protocol unit equal to 1 metric ton of carbon dioxide equivalent. RMUs are generated in Annex I Parties by LULUCF activities that absorb carbon dioxide.

Residual feed intake The difference between an animal's actual feed intake and its expected feed requirements for maintenance and growth.

Resilience The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner.

Resurgence Abnormal increase in pest populations often exceeding the economic threshold level, following the insecticide application.

Ridge tillage Ridge-till involves planting seeds in the valleys between carefully molded ridges of soil. The previous crop's residue is cleared off ridgetops into adjacent furrows to make way for the new crop being planted on ridges. Maintaining the ridges is essential and requires modified or specialized equipment.

Rio Conventions Three environmental conventions, two of which were adopted at the 1992 "Earth Summit" in Rio de Janeiro, the United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Biodiversity (CBD), while the third, the United Nations Convention to Combat Desertification (UNCCD), was adopted in 1994. The issues addressed by the three treaties are related – in particular, climate change can have adverse effects on desertification and biodiversity – and through a Joint Liaison Group, the secretariats of the three conventions take steps to coordinate activities to achieve common progress.

Rio+20 The United Nations Conference on Sustainable Development, to be held in Rio de Janeiro, Brazil, on June 4–6, 2012. The first UN Conference on Sustainable Development was the "Earth Summit," held in 1992, and it spawned the three "Rio Conventions" – the UNFCCC, the UNCCD, and the UNCBD.

Riparian Relating to land adjoining a stream or river.

Risk The combination of the probability of an event and its negative consequences.

Risk assessment A methodology to determine the nature and extent of risk by analyzing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed people, property, services, livelihoods, and the environment on which they depend.

Salinization The accumulation of salts in soils.

Second Assessment Report (SAR) An extensive review of worldwide research on climate change compiled by the IPCC and published in 1995. Some 2,000 scientists and experts participated. The report is also known as Climate Change 1995. The SAR concluded that “the balance of evidence suggests that there is a discernible human influence on global climate.” It also said that “no-regret options” and other cost-effective strategies exist for combating climate change.

Sensitivity (to climate variability or change) Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise).

Silviculture Silviculture is the art and science of growing and maintaining trees.

Sink Any process, activity, or mechanism which removes a greenhouse gas, an aerosol, or a precursor of a greenhouse gas from the atmosphere. Forests and other vegetation are considered sinks because they remove carbon dioxide through photosynthesis.

Small holder The definition of small holders differs between countries and between agro-ecological zones. In favorable areas of small holder subsistence agriculture with high population densities, small holders often cultivate less than one hectare of land, whereas they may cultivate ten hectares or more in semiarid areas or manage up to ten heads of livestock.

Social protection Initiatives that provide income (cash) or consumption (food) transfers to the poor, protect the vulnerable against livelihood risks, and enhance the social status and rights of the excluded and marginalized.

Soil health The capacity of soil to function as a living system.

Soil organic matter (SOM) Soil organic matter is any material produced originally by living organisms (plant or animal) that is returned to the soil and goes through the decomposition process. At any given time, it consists of a range of materials from the intact original tissues of plants and animals to the substantially decomposed mixture of materials known as humus.

Soil structure Soil structure is defined by the way individual particles of sand, silt, and clay are assembled. Single particles when assembled are called aggregates. Aggregation of soil particles can occur in different patterns, resulting in different soil structures.

Soil texture Texture indicates the relative content of particles of various sizes, such as sand, silt, and clay in the soil.

Strip tillage Strip tillage involves tilling the soil only in narrow strips with the rest of the field left untilled.

Subsoiling or ripping Soil preparation treatment done with tined implements to break up hard pans without turning the soil upside down.

Supplementary irrigation The process of providing additional water to stabilize or increase yields under site conditions where a crop can normally be grown under direct rainfall, the additional water being insufficient to produce a crop. The concept consists in making up rainfall deficits during critical stages of the crops in order to increase yields.

Supply chain The full range of activities, which are required to bring a product or service from conception, through the different phases of production (involving a combination of physical transformation and the input of various producer services), delivery to final customers, and final disposal after use.

Sustainability (economic) A situation whereby: (1) the value added resulting from upgrading in the value chain (additional profits, wages, taxes, consumer value) is positive for each stakeholder in the extended value chain whose behavior (in terms of upgrading) is expected to change in order to create the additional value; and (2) the generation of added value sets in motion, or speeds up, a process of growth and structural transformation.

Sustainability (environmental) Meeting the needs of the present without compromising the ability of future generations to meet their needs.

Sustainable and inclusive value chain development The full range of farms and firms and their successive coordinated value-adding activities that transform raw agricultural materials into food products that are sold to final consumers and disposed after use, in a manner that is profitable throughout the chain, has broad-based benefits for society and does not permanently deplete natural resources.

Sustainable development Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Sustainable use of genetic resources The use of components of biological diversity in a way and at a rate that does not lead to the long-term decline of biological diversity, thereby maintaining its potential to meet the needs and aspirations of present and future generations.

System of rice intensification (SRI) SRI is a methodology for increasing the productivity of irrigated rice cultivation by changing the management of plants, soil, water, and nutrients. SRI practices lead to healthier, more productive soil and plants by supporting greater root growth and by nurturing the abundance and diversity of soil organisms.

Technology transfer A broad set of processes covering the flows of know-how, experience, and equipment for mitigating and adapting to climate change among different stakeholders.

Third Assessment Report (TAR) The third extensive review of global scientific research on climate change, published by the IPCC in 2001. Among other things, the report stated that “The Earth’s climate system has demonstrably changed on both global and regional scales since the pre-industrial era, with some of these changes attributable to human activities. There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities.” The TAR also focused on the regional effects of climate change.

Transgenic plants Transgenic plants are plants possessing a single or multiple genes, transferred from a different species.

Univoltine Refers to organisms having one generation per year.

Vernalization In some crops derived from winter grasses (e.g., winter wheat), full flowering does not occur unless the plant experiences a period of cold temperature.

Voltinism Indicates the number of generations of an organism per year.

Vulnerability The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.

Water scarcity The point at which the aggregate impact of all users impinges on the supply or quality of water under prevailing institutional arrangements to the extent that the demand by all sectors, including the environment, cannot be fully satisfied.

Water-use efficiency Water-use efficiency means lowering the water needs to achieve a unit of production in any given activity.

Water vapor (H_2O) An important greenhouse gas in the troposphere that also plays a role in ozone depletion chemistry in the stratosphere.

Watershed A topographically delineated area that is drained by a stream system, i.e., the total land area that drains to some point on a stream or river. The watershed is a hydrologic unit that has been described and used as a physical–biological unit and a socioeconomic–political unit for planning and managing of natural resources.

Weather Weather is the brief, rapidly changing condition of the atmosphere at a given place and time, influenced by the movement of air masses.

Weather-index insurance A class of insurance products that can allow weather-related risk to be insured in developing countries where traditional agricultural insurance may not always be feasible, thereby helping to increase farmers' ability (and willingness) to invest in measures that might increase their productivity.

Wetlands An area of land whose water table is at or near the surface. Typically inundated with water, these shallow water regions cover approximately 6 % of the earth's surface and have high levels of net primary productivity. Wetland emission of methane is an important source of this greenhouse gas.

Zero tillage No-till farming (sometimes called zero tillage) is a way of growing crops from year to year without disturbing the soil through tillage.

Annexure II

Acronyms

ACT Africa Conservation Tillage Network
ACZ Agroclimatic Zone
AICRIP All India Coordinated Rice Improvement Project
AMF Arbuscular Mycorrhizal Fungi
AOSIS Alliance of Small Island States
AR4 Fourth Assessment Report
ARPPIS African Regional Postgraduate Programme in Insect Science
ASA Articulação no Semi-Árido
AVRDC Asian Vegetable Research and Development Center
AWD Alternate Wetting and Drying
AWM Agricultural Water Management
BNF Biological Nitrogen Fixation
BOD Biochemical Oxygen Demand
BSATs Brazilian Semiarid Tropics
Bt *Bacillus thuringiensis*
CAST Council for Agricultural Science and Technology
CBD Convention on Biological Diversity
CDM Clean Development Mechanism
CER Certified Emission Reductions
CFCs Chlorofluorocarbons
CH_4 Methane
CHM Crop Health Management
CIMMYT International Maize and Wheat Improvement Center
CO_2 Carbon Dioxide
CO_2e Carbon Dioxide Equivalent
COD Chemical Oxygen Demand
CRA Climate-Resilient Agriculture
CRF Common Reporting Format
CSISA Cereal Systems Initiative for South Asia
DCD Dicyandiamide
DSS Decision Support System
EAIS East Antarctic Ice Sheet
EBPM Ecologically Based Pest Management
EEZ Exclusive Economic Zones
EGTT Expert Group on Technology Transfer
ENSO El Niño–Southern Oscillation
EPM Ecologically Pest Management
EPSP Enolpyruvylshikimate-3-Phosphate
ERU Emission Reduction Unit
EU European Union
EWS Early Warning System
FACE Free Air Gas Concentration Enrichment
FAO Food and Agriculture Organization of the United Nations
FAO–PAR FAO–Platform for Agrobiodiversity
FAOSTAT FAO Statistical Yearbook
FCM Fat Corrected Milk
FPCM Fat and Protein Corrected Milk
GATT General Agreement on Tariffs and Trade
GCF Green Climate Fund
GCMs General Circulation Models
GDP Gross Domestic Product
GDR German Democratic Republic
GEF Global Environment Facility
GHGs Greenhouse Gases
GIS Geographic Information System
GIS Greenland Ice Sheet
GISS Goddard Institute for Space Studies (part of NASA)
GMO Genetically Modified Organisms
GNP Gross National Product
GPS Global Positioning System
Gt Gigatons
GWP Global Warming Potential
HFC Hydrofluorocarbons
HLPE High Level Panel of Experts
ICIPE International Centre of Insect Physiology and Ecology
ICT Information and Communications Technology

ICTSD	International Centre for Trade and Sustainable Development
IEA	International Energy Agency
IFAD	International Fund for Agricultural Development
IFPRI	International Food Policy Research Institute
INCID	Indian National Committee on Irrigation and Drainage
INM	Integrated Nutrient Management
IPCC	Intergovernmental Panel on Climate Change
IPM	Integrated Pest Management
IRRI	International Rice Research Institute
IWM	Integrated Weed Management
IWMI	International Water Management Institute
KCCS	Kisan Credit Card Scheme
LCA	Life Cycle Assessment
$N_2$0	Nitrous Oxide
NAIS	National Agricultural Insurance Scheme
NAMAs	Nationally Appropriate Mitigation Actions
NGOs	Nongovernmental Organizations
NOAA	National Oceanic and Atmospheric Administration
O_3	Ozone
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of Petroleum Exporting Countries
PAHs	Polycyclic Aromatic Hydrocarbons
PFC	Perfluorocarbon
POA	Program of Action
PTGS	Posttranscriptional Gene Silencing
RCTs	Resource-Conserving Technologies
REDD	Reducing Emissions from Deforestation and Forest Degradation
REDD+	Reducing Emissions from Deforestation in Developing Countries, Including Conservation
SAR	Second Assessment Report
SCCF	Special Climate Change Fund
SFC	Standard Fog Collectors
SHGs	Self-Help Groups
SIDS	Small Island Developing States
SLM	Sustainable Land Management
SOC	Soil Organic Carbon
SP-IPM	Systemwide Program on Integrated Pest Management
SRB	Sulfate-Reducing Bacteria
SRES	Special Report on Emissions Scenarios
SSWM	Site-Specific Weed Management
SVOCs	Semi-Volatile Organic Compounds
TAR	Third Assessment Report
TGT	Temperature Gradient Tunnel
UKMO	Global Weather Forecast Model from the “UK MetOffice”
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USDA	United States Department of Agriculture
US-EPA	United States Environmental Protection Agency
VOCs	Volatile Organic Compounds
WAIS	West Antarctic Ice Sheet
WEY	Wheat Equivalent Yield
WTO	World Trade Organization
YRR	Yield Reduction Rate
ZT	Zero Tillage

Reference

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